HEALTHY SOILS, HEALTHY PLANTS, HEALTHY HUMANS

A HOLISTIC EXPLORATION OF SUSTAINABLE INTENSIFICATION EFFECTS ON FARMING SYSTEMS IN MALAWI

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PROJECT TITLE

Healthy soils, healthy plants, healthy humans: A holistic exploration of sustainable intensification effects on farming systems in Malawi

OPERATIONALIZATION

Social-Ecological Systems (SES)	A geographically explicit unit that can be distinguished by its specific set of environmental and social components, the combination of which creates distinct patterns of human resource interactions (Ostrom, 2009).
Farm household	Defined as a family-run enterprise, the household managing it and the off-farm income-generating activities by household members (Ditzler et al. 2018, 2019)
Treatment type	Refers to the farmer groups within the AfricaRISING project. This would either be mother-trial, baby-trial, or local control.
Smallholder Farmer	A crop or livestock farmer practicing a mix of commercial and subsistence production with less than 2 hectares of land. Where the family provides most of the labour and the farm provides the principal source of income (Narayaran and Gulati 2002)
Mother-trial Farmer	Mother-trial farmers are those who have implemented a range of sustainable intensification technologies on their farms, and have high rates of exposure to researchers and extension officers from the Africa RISING ESA project.
Baby-trial Farmer	Baby-trial farmers are a selected group of farmers associated with a mother trial.
Local control	These are farmers that are located within villages that have participated in Africa RISING activities but are farms that have not directly benefited or been exposed to Africa RISING technologies.

ACRONYMS & ABBREVIATIONS

- Sub-Saharan Africa **(SSA)**
- Sustainable Development Goals **(SDGs)**
- Social-Ecological Systems **(SESs)**
- The Africa Research in Sustainable Intensification for the Next Generation **(Africa RISING)**
- Africa RISING East and Southern Africa Project: Sustainable Intensification of cereal-legume-livestock integrated farming systems in East and Southern Africa **(ESA)**
- United States Agency for International Development **(USAID)**
- International Institute of Tropical Agriculture **(IITA)**
- International Food Policy Research Institute **(IFPRI)**
- Sustainable Intensification **(SI)**
- Participatory Action Research **(PAR)**
- Farm Input Subsidy Program **(FISP)**
- Biological nitrogen fixation **(BNF)**
- Nitrogen **(N)**
- Carbon **(C)**
- Soil Organic Carbon **(SOC)**

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ABSTRACT

Smallholder farmers in Malawi are faced with resource and space constraints, low soil fertility, and vulnerability to climatic shocks. This has led to poor nutritional standing of farmers and their households, and very little ability to break through experienced feedback loops that keep them locked in a state of food and resource insecurity.

The connection between soil-land and the human-health axis is only recently gaining momentum, however promising programs focused on sustainable intensification (SI) have begun to be implemented in sub-Saharan Africa to address root causes that lead to multi-dimensional poverty. Approaches such as SI, aim to provide farmers with low-cost accessible technologies that have the potential to optimize spatial resource allocation, increase production, and harness natural processes to mend degraded soils.

As there are many SI technologies the scope of this research was to understand the holistic effect that incorporating biologically nitrogen fixing legumes within crop configurations can have on a farm system. Specifically by looking at the differences in space allocated to legume intercropping in the form of legume-legume, maize-legume, and doubled-up legume rotations (DLR).

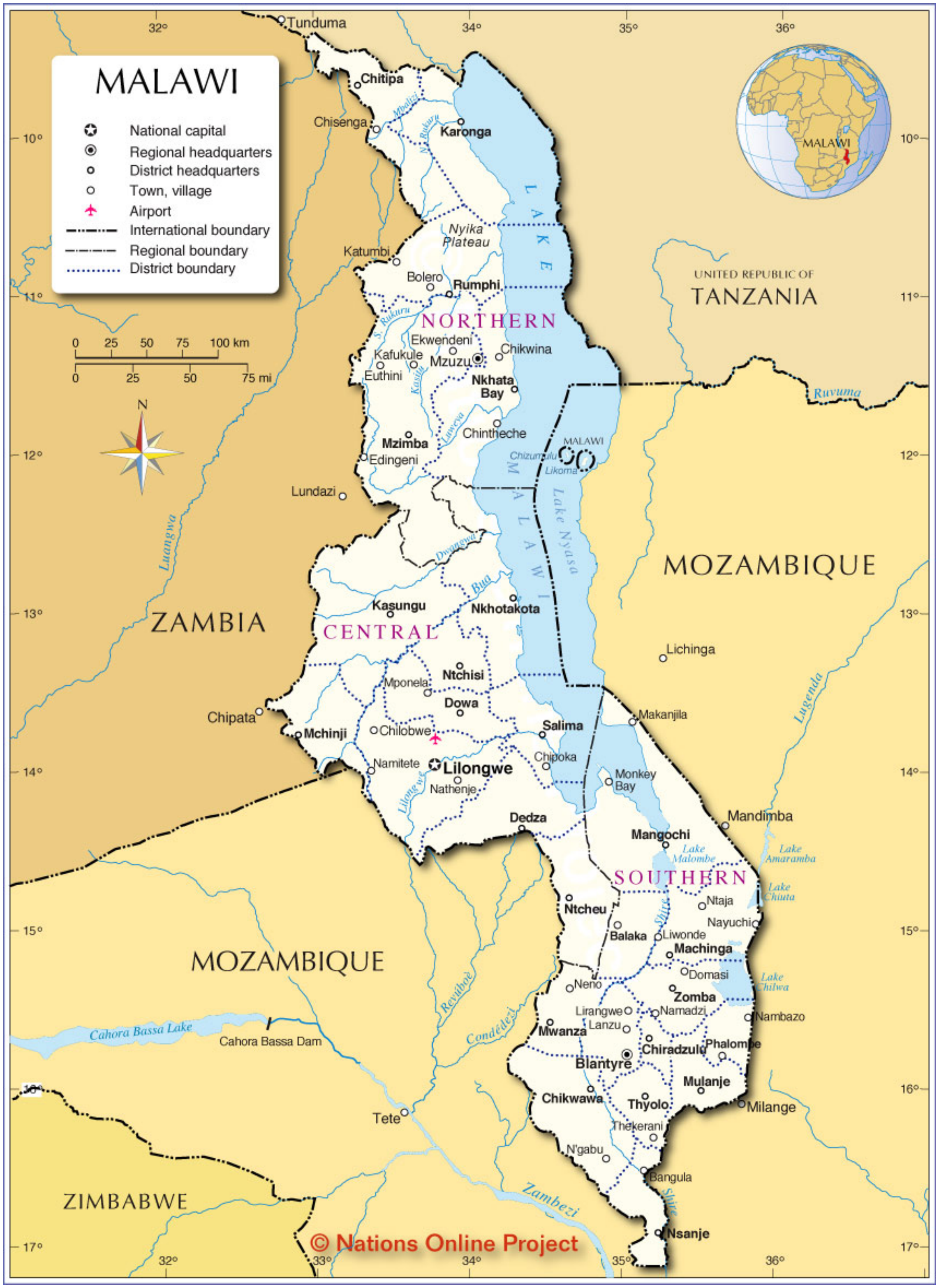
Due to the complex and dynamic nature of farming systems, one change in management may lead to spillover effects throughout the entire farming system. Therefore it was essential that a systems approach was used to analyze not just lower scale processes within the soil, but also higher-level analysis at the household and farm level. To do this, the application of an innovative bio-economic model, FarmDESIGN was employed, which allows for the integration of data at multiple levels.

A case study approach was taken between two treatment groups (a mother and baby farm) in Central Malawi, with an additional exploration component carried out to understand potential opportunities, tradeoffs, and synergies that exploratory farm configurations could generate. In the case study analysis of the two treatments, a clear trade off was seen between farms that adopt more space for cash crops, and those that adopt more space for legume-intercropping. With a greater area dedicated to cash crops associated with increased financial standing, but less improvement in soil organic matter and dietary energy yield. While the farm with more space allocated to legume intercropping, was associated with increased levels of environmental and nutritional standing, evidenced by the indicators of increased soil organic matter, and increased dietary energy yield.

In exploratory runs the results show when optimizing holistic objectives of nutrition, economic, environment, and social standing the model allocates increased space to legume intercropping configurations. For the mother farm this was seen in increased area to DLR and for the baby farm, legume-maize area. It can be concluded from this that a farms holistic standing increases the more area there is dedicated to legume intercrops.

GRAPHIC SUMMARY

The following depicts general project locations, and project sites within Malawi:



1.0 INTRODUCTION

The problem of food security remains an urgent issue in Sub-Saharan Africa (SSA), with an estimated 1 in 3 people suffering from hunger (Bezner Kerr et al., 2019; FAO et al., 2017). Ending hunger worldwide has been an international goal for years, most recently highlighted by the Sustainable Development Goals (SDG2) calling for Zero Hunger for all by 2030 (Perez-Escamilla, 2017). Reaching this goal has remained pervasive due to increasing demands in food caused by population growth, ever changing climatic conditions and more severe El Nino weather cycles experienced, leading to malnutrition rates that hover stubbornly high (FAO, 2018; Mungai et al., 2016).

These macro scale shifts are coupled with regional changes in farming management which have led to a decrease in soil fertility due to an emphasis on external inputs and the expansion of monocrop cereal-based systems (Snapp et al., 2018). Positive feedback loops in the environment between the land and atmosphere only work to lock the system into a state of degradation, while social feedback loops of limited resources and knowledge of best practices, allow for little change to take place by the farmers themselves (Giller et al., 2006; Mungai et al., 2016).

In order to break this cycle of insecurity, farmers must not only adapt to new conditions, but must find ways to produce more while increasing their lands fertility and sustaining the resources they depend upon (Giller et al., 2011; Godfray et al., 2010).

The difficulty of these challenges has become increasingly clear over the past decade and has led to new approaches in many development projects. With an issue like food security, there are multiple social-ecological entry points and objectives that can be used to initiate change (Snapp et al., 2018). This is evidenced in the evolution of development policy from direct food aid, towards economic support, to the most recent shift towards farm specific objectives (FAO et al., 2017).

Initiatives such as agroecology, climate smart agriculture, and sustainable intensification (SI) have been proposed as a way to increase the production of food, fuel, and fiber by providing farmers with the tools to manage their lands in a sustainable way (Campbell et al., 2014; Mungai et al., 2016; Snapp et al., 2018). Through SI, the foundation of a farm-system, the soil, is targeted to generate change (Snapp et al., 2018). This is done by increasing nutrient flows, and building up essential nutrient stocks within the soil so that its ecosystem services such as plant production can be optimized without extensive external inputs (Giller et al., 2015). Within African maize systems, SI activities have been predominately focused on introducing green manures, diversification with grain legumes, and nutrient management with mineral and organic fertilizers (Droppelmann et al., 2017; Timler et al., 2017).

SI is a promising approach based on theory, however there is little known about the actual effects on the whole-farm, as only recently the connection between our soil and our lands have been linked to outcomes such as increased social, environmental and human health (Snapp et al., 2018). One reason for this gap in research is due to the constraints that arise when trying to carry out systems analysis for farms. As farms are highly complex and dynamic, with interactions and resource flows that are constantly taking place between different hierarchical levels and at different temporal scales (Giller et al., 2011). Therefore, it is essential to build methods and knowledge surrounding SI activities and their effects at the farm-scale, to see impacts at an aggregate level, and how interventions at lower levels (i.e. crops) may interact.

Significant research has been conducted on the adoption of and results of increased agroecological practices within Africa (Mungai et al., 2016). However this research is most often focused on identifying productivity and environmental impact. Field-based assessments of SI must move beyond just environmental indicators but include indicators that speak to the whole farm system (Snapp et al., 2018). Conducting analysis at the farm-scale, where environmental, economic, social, and nutritional aspects are holistically explored, is essential as it is at the farm level where farmers will feel immediate and long-term results and base their management decisions from (Bezner Kerr et al., 2019).

1.1 Research Problem

Farms themselves, are agroecosystems, created from the interaction of a hierarchy of components, most notably plants, animals, and humans, imbedded within social-ecological systems (SESs) (Fresco, 1988; Ostrom, 2009). This makes for highly complex, heterogeneous, and dynamic farms (Tittonell el al., 2010). A systems approach can provide researchers with a framework to analyze potential impacts experienced at the farm-level (Ostrom, 2009). So not just one component is considered, but all prominent components and their interactions are (Ostrom, 2009). This makes room in analysis for the potential synergies, tradeoffs, and emergent properties that may arise based on system characteristics (Ditzler et al., 2019).

With the adoption of a systems framework there must be the ability to integrate multiple components of a system and their effects on the whole. To do this a variety of constraints arise, as data must be integrated at multiple levels and over different timescales. To look at these constraints more closely: SI works to target a range of multi-level entry points to insight change, but a core part of this change takes place within the soil and field level by increasing nutrient cycling through management (Campbell et al., 2014). In order to disentangle effects of SI technologies at the farm-scale, therefore lower scale processes (i.e. at the soil, plant, animal, field, and household level) must be upscaled to allow for higher-level analysis.

Furthermore, these multi-level interactions are also taking place at different time scales and both short-term changes and potential long-term shifts will need to be assessed to fully understand SI technology effects on the system. This is important as farmers will need to see immediate change for SI technologies to be adopted, but also slower changes such as the accumulation of soil carbon, soil organic matter, and nitrogen can speak to long term system resilience and should eventually lead to farm-scale effects in the environmental, social, nutritional, and economic standing of a farm (Mungai et al., 2016; Petersen and Snapp, 2015).

1.2 Research Aim

Overall, this research aims to determine the potential farm-scale effects SI technologies can have on farms in Central Malawi, by holistically looking at the farms environmental, social, nutritional, and economic standing. This research will analyze farms by that of treatment group and agro-ecological zone to understand how potential heterogeneity that can arise from these groups may lead to different reactions in response to implemented SI technologies.

1.3 Research Objectives

RO1. To assess the overall farm balance of the environmental, social, nutritional, and economics of the farm, through the use of indicators at both the field and household level;

RO2. To analyze the differences between treatment type and their influence on SI activity outcomes;

RO3. To assess potential drivers for adoption of technologies from the farmers point of view.

1.4 Hypotheses

The following hypotheses are in-line with the above research objectives.

1. SI technologies implemented in farms will show improvements in the categories of environmental, nutritional, and economic standing, however social standing due to labour requirements of SI cropping configurations will not be improved.

2. The more SI technologies implemented the more positive effect the overall farm scale will see, as technologies will build upon each other. Therefore treatment groups will show differences, with mother farmers experiencing the most positive change.

3. Adoption reasons will be in line with previous research, differences will be seen between the agro-ecological zones and treatment types, as farmers may be more cautious to adopt new technologies when previous farming has been difficult or farm-scale effects have not been felt yet.

PART ONE

2.0 RESEARCH CONTEXT

This research is embedded within the Africa RISING East and Southern Africa Project: *Sustainable Intensification of cereal-legume-livestock integrated farming systems in East and Southern Africa (ESA)*, a project focused on implementing SI farming technologies in Southern Africa (SA) (IITA, 2015). ESA project activities have focused on SI technologies that increase the productivity of farm components in maize-based systems. Working in a way that supports the continued production of maize due to its critical role in calories consumed while also introducing innovative and cost-efficient solutions to increase both soil fertility and nutrition of the farm household (Smith et al., 2016; Snapp et al., 2018).

The ESA project has locations in Malawi, Zambia, and Tanzania; however this research will strictly focus on the Malawi context.

2.1 Malawi

Within Malawi, they have a saying: 'Chimanga ndi moyo,' which translates to 'maize is life.'

Malawi has an estimated population of 17 million, with 80% of whom live in rural areas and depend upon agriculture for food and livelihoods (Bezner Kerr et al., 2019; World Bank, 2017). This is coupled by the fact that population densities have continued to rise, with a population growth rate of 3.3%, placing enormous pressure on the land (Snapp et al., 2018; World Bank, 2017). Due to the fact that the majority of farmers in Malawi are characterized as smallholder, with farm sizes on average of less than 1 ha, it has been difficult to respond to the increasing calorie demands (Snapp et al., 2018). As 50.7% of the population currently are living below the poverty line, the situation is only set to worsen (Kerr et al., 2019; World Bank, 2017).

In Malawi, it is estimated that 70% of all arable land is devoted to maize production, and the importance of maize as a crop both nutritionally and culturally, is not to be underestimated (Peter, Messina, and Snapp et al., 2018). However, a system dominated by maize has effects that can spill into environmental, social, nutritional, and economic domains of a society, as sole crop systems not only decrease on-farm functioning but also what is sold and consumed (Ortega et al., 2016). Evidence of this is the fact that production rates have seen a steady decrease over time even with increased area given to maize crops, due to the high nutrient demands of maize which have mined the soil of its nitrogen (Messina et al., 2017; Ortega et al., 2016; Snapp eta l., 2018). This has led to the need for continuous cultivation to maintain the original production levels, without allowing for periods of fallow, only furthering the cycle of degradation (Morton, 2007; Ortega et al., 2016; Snapp et al., 2010).

Land-use has also shifted from biodiverse systems to those where lesser-known crops and livestock have been pushed out leading to decreases in biodiversity and soil fertility (Kerr et al., 2019). A decrease in biodiversity creates more vulnerable farms to disturbances (i.e. drought, pests, and diseases) as there is only one main crop in the field (Peter, Messina, and Snapp, 2018; Morton, 2007). It also has implications to soil fertility, because without livestock or crop residue inputs, it is difficult to increase nutrients without the application of mineral fertilizer, which is often not an option due to resource constraints (Peter, Messina, and Snapp, 2018).

Regarding health and nutritional implications, Malawi has been characterized with high malnutrition rates, with over 40% of all households experiencing chronic food deprivation and a deficiency in vitamin A and iron (FAO et al., 2017). The typical Malawian diet is approximately 52% maize based, usually consumed through a porridge (Nsima), served at almost every meal (Timler et al., 2017). However, maize is poor in amino acids, essential micronutrients, fiber and protein making it necessary for other foods to be consumed alongside maize for basic nutrition needs to be met (Kerr et al., 2019; World Bank, 2005). This is especially important for children, and pregnant mothers (FAO et al., 2017; Kerr et al., 2019).

2.2 Africa RISING East and Southern African Project

The ESA Africa RISING project works to use the agriculture-nutrition nexus as an entry point to insight change in multiple domains, with sustainable intensification at its core (IITA, 2015). The overarching objective of the ESA project is to increase food production, livelihoods, and food security, while improving the natural resource base (IITA, 2015; 2017). The project has a range of crosscutting projected outcomes, that hit on multiple sustainability domains being productivity, economic, social, human, and environmental (IITA 2017).The project aims to identify and validate scalable options for sustainable intensification within cereal-based farming systems with the end goal of reaching at least 300,000 smallholder farm households by 2021 (IITA, 2017).

The project is funded by USAID under the Feed the Future initiative and was implemented by a range of partners, at the global, national, and local scale, with the International Institute for Tropical Agriculture (IITA) leading implementation and the International Food Policy Research Institute (IFPRI) responsible for data management, evaluation, and impact assessment. Additional research and expertise were provided by Michigan State University (MSU) (IITA, 2017). The project was implemented in phases, with the first phase implemented in 2011 and the second, starting in 2016 and finishing in 2021. Phase 1 focused on understanding best technologies that smallholder farm families could adopt and Phase 2 on implementing the identified technologies (IITA, 2015). This research will take place at the end of Phase 2, to assess farms within the 2019/2020 cropping season. Within the ESA project a variety of technologies, hereon referred to as 'SI technologies,' seen in Table 2, were implemented. Due to the existent heterogeneity within the sub-Saharan region, different activities and technologies were implemented so as to ensure only context-appropriate technologies were applied (Dropelmann, Snapp, Waddington, 2017). The technologies chosen for Malawi, were based on identified entry points for maize based farms, and chose to focus on: fertilizer use, introduction of legumes and their biomass, and residue management practices (Mungai et al., 2016).

Table 1: SI Technologies Implemented in Malawi through the ESA project (IITA, 2015)

Technology	Validated technology
Genetic integration involving introduction of new crops and varieties to overcome existing biotic and abiotic stress	-Climbing bean -Short duration pigeon pea
Manipulation of crop ecologies to get more crops on limited land and maximize biological nitrogen fixation	-Doubled-up food legumes -Cereal-legume intercropping, crop rotations
Integrated soil fertility management as a cost-effective approach to replenish soil fertility	-Optimized fertilizer rates, -composts
Improved livestock feed quality and quantity	-Quality forage and fodder-based feed rations -Livestock feed with fodder rations

3.0 THEORETICAL FRAMEWORK

The theoretical framework will first describe the smallholder farmers in Malawi, and then address conceptual terms such as soil fertility, legume-intercropping, biological nitrogen fixation and doubled up legume intercropping which are relevant to the SI technologies implemented. Following this, relevant literature will be summarized in regards to implemented SI technologies and results seen in similar case studies, including the exploration of barriers that farmers face in long-term SI adoption.

3.1 Smallholder Farmers in Malawi

Smallholder farmers in SSA are highly diverse and heterogenous (Giller et al. 2011; Tittonell et al., 2005; Zingore et al., 2008). Each farmer, like all of us, has their own dreams and aspirations, as well as, a set number of available resources, such as land, labor, and financial assets that they can utilize to realize their dreams (Timler et al., 2017). Hence, acknowledging this diversity, and responding to the evident variability between farms must be a central component in any steps taken to engage in research within this setting.

Typologies are essential to furthering SI research in their ability to categorize some of the complexity seen within the SSA context, and provide guidance for strategies that are tailored to farm-specific recommendations rather than blanket approaches (Chikowo et al., 2014; Birthe et al., 2020; Tittonell et al., 2010). Differentiating between farm types can also allow for more accurate analysis of the effects SI technologies have had on a farm. Therefore previous studies in Malawi focused on characterizing the heterogeneity of farmers through typologies will be leveraged in this research to provide an already evidenced set of categories that most smallholder farmers in Malawi can fit within (Timler et al., 2017; Chikowo et al., 2014; Snapp et al., 2019). These typologies are notably based on resource endowment in terms of land, labour, and capacity for investment (Giller et al., 2011).

Within Malawi, investigations completed by Chikowo et al., (2018; 2014) and Kamanga et al., in 2009 and 2011 provided 3-5 typologies which can represent the levels of resource endowment within the country. These categories range between resource-endowed famers to resource-constrained farmers. With findings that show 5% of Malawian farmers characterized as high resource; 10% as medium resource; 47% as low resource; and 38% as least -resource (Kamanga et al., 2009; Kamanga, 2011). Although multiple groupings exist, it is important to note that the majority of farmers within Malawi, exist somewhere within the spectrum of resource constrained (Chikowo et al., 2018). Resource constrained farmers, will have large food deficiencies due to poor crop yields, and will most likely supplement their farm income through *ganyu* a practice of working on resource endowed farmers' fields or through other means (Chikowo et al., 2014).

Farm types also can point to indications of soil fertility levels within a farm as constrained farmers will not have the same opportunities to invest in improved seeds or fertilizer (Chikowo et al., 2014). As previous land management can be linked to different soil fertility levels, and land management can be linked to farm types, this could have significant impacts on the results of SI technologies implemented at a farm. For example, this can be seen in the fact that resource endowed farmers will have had previous access to more nutrients through fertilizer and increased livestock for manure leading to higher levels of soil organic carbon and P already within their farm's soils (Timler et al., 2017).

3.2 Farm-Scale Research

Farm-scale research is important, as although SI technologies can have significant impacts at the field level, it is the farm-scale where farmers will evaluate the impacts and constraints they encounter (Ditzler et al., 2019; Giller et al., 2011).

In short term, at the farm level, the key actor is the farmer themselves, as they will feel the immediate impact, with their ability to make decisions, and manage the farm. This feeling directly comes from their available household budget, their household nutrition, and their household labor. These modules are based on household and field level indicators which when modeled can show the flow of resources between the field, house, and market. What they produce, what they can consume, and what they sell, and what they need to add to their farm to ensure this cycle continues.

In medium term, effects of SI technologies at the farm scale, are specifically focused on risk avoidance. Can the farm produce more, and store more food to remain resilient?

In long term, it is field level flows of resources and nutrient buildup that will eventually affect the whole farm. As a farm begins to act more efficiently, rates in productivity will increase, including food and profitability, and necessary inputs for previous productivity levels will decrease.

3.3 The Problem of Soil Fertility

Soil fertility refers to the ability of soil to sustain plant growth by providing plants with essential nutrients, and favorable chemical, physical, and biological characteristics for growth (FAO, 2020). The main function provided by fertile soils is its provisioning of food (FAO, 2020). It is difficult to address the problem of low soil fertility as it is the result of multiple causes, and also due to our continued needs in meeting global food demands. Large expanses of land are now characterized as degraded, and Malawi is no different.

A range of interactions taking place at multiple scales between different environmental and social processes have led to degraded lands that are poor in fertility. Soil fertility is not just affected by micro level shifts, such as how farmers farm, but is also influenced by macro level interactions which make it difficult to address the issue of soil fertility without considering the environment it is embedded within (Kebede et al., 2019).

At the macro level, SSA is especially vulnerable to both physical and social changes due to the challenging biophysical characteristics of the system making the countries extremely sensitive to land degradation (Falkenmark and Rockström, 2008). The continued ramifications of climate change, such as unpredictable rainfall and increased droughts, will likely only intensify due to the challenging biophysical environment where access to water is low and conditions for ecosystems to tip towards drought are high (Giller et al., 2011). At the regional level, increasing populations has strained the land leading to micro level changes in management to deal with increasing food demands and decreasing productivity levels such as the hand-hoe management which involves leading the soil bare after harvest, tillage, and no fallow periods continue to worsen the situation (Gwenambira, 2015).

However, the current paradigm in addressing fertility constraints has focused on increased inputs. In the Western world this has translated to Inorganic N and mineral fertilizer, and although less so in SSA, the application of mineral fertilizer has been promoted as a solution for low production levels. Evidenced by the Government of Malawi's Farm Input Subsidy Program (FISP) promoted since 2005 which has reached between 76-92% of the farmers in this research (Snapp et al., 2018). This has provided 1.5 million households with fertilizer and hybrid maize seeds (Chirwa and Dorward, 2013; Kerr et al., 2019; Mungai et al, 2016). Results of this have been mixed and there are potential and dangerous tradeoffs with the application of fertilizer (Kerr et al., 2019). The use of mineral fertilizer can play a critical role when used appropriately, however it is difficult to control nutrient losses during the application, which can lead to excess of N, P, and CO2 entering the atmosphere (Bindraban et al., 2020). In addition to this, fertilizer can have harmful implications to the animal and human health, and decrease natural system balancers such as agrobiodiversity (Kebede et al., 2019).

3.4 Introduction of Legumes into Maize Systems

Introducing legumes into agricultural systems, can increase nutrient flow for multiple hierarchical levels within the farm: for humans, by an additional food source; for livestock, through crop biomass as feed; and for the soil, through nitrogen fixation (Smith et al., 2016; Timler et al., 2017). Even with these promises, and the soil fertility improvements that legumes can bring, farmers often choose not to prioritize new crops for fear of limiting their maize production, which historically is how they have survived (Snapp et al., 2002). This is seen in Malawi, where after a decade of promotion, farm area devoted to legumes remains below 25% (Mhango, Snapp, & Phiri, 2013). Therefore SI has focused on the incorporation of legumes into maize systems, to ensure that the risk taken is not as large, and food crop production is not compromised (Smith et al., 2016).

3.4.1 Biological Nitrogen Fixation

Within agriculture in Southern Africa, soils are characterized with high levels of nitrogen (N) deficiencies which can act as a major limiting factor in plant growth (Mhango, Snapp, and Kanyama-Phiri, 2017). Therefore the introduction of N within soils is an important component of farm management, especially within high demand crop systems such as maize (Gwenambira, 2015). However, with 47% of smallholder farmers in Malawi characterized as low resource, finding ways to address soil fertility without the expenditure of limited funds on inorganic fertilizer is essential (Chikowo et al., 2014; Snapp et al., 2018).

As stated, prior solutions for poor soil fertility and N deficiencies have been largely based on the increase use of inputs through the application of inorganic fertilizers. This however is unsustainable in resource constrained settings and an excess use of inorganic fertilizer can lead to potentially dangerous impacts to the environment and biodiversity within the system (Bindraban et al., 2020).

Methods to increase N without external inputs for farmers can be seen through the adoption of management practices such as the application of compost and livestock manures, or through the integration of legume crops (Mhango, Snapp, and Kanyama-Phiri, 2017). Leguminous crops have been shown to act as an N source for above and below ground biomass due to their ability to biologically fix nitrogen and recycle nutrients from deeper subsoil levels that most low rooted crops cannot reach (Gwenambira, 2015). This allows for their growth in low fertile soils, while also replenishing soil nitrogen stocks, building SOM through crop residue, and providing N for nearby crops (Phiri, Kanyama-Phiri, and Snapp, 1999; Mhango, Snapp, and Kanyama-Phiri, 2017; Snapp et al., 2010; Timler et at al., 2017).

Traditionally intercrop systems consist of maize and legumes, with the proportion of each species dependent upon the main interest of the farmers (Gwenambira, 2015). Maize and legumes have researched evidence of complementary growth habits and resources needs, therefore optimizing space and resources, while minting the same yields per area that a sole-maize crop would have (Mhango, Snapp, and Kanyama-Phiri, 2017). In Malawi legumes grown can include: groundnut, common beans, soybean, pigeonpea, and cowpea (Gwenambira, 2015). The amount of N fixed by legumes is based by plant species, management, and biophysical factors, with groundnuts having the ability to fix between 32 to 206 kg N ha-1and pigeonpea 69 to 100 kg N ha-1, with more net contribution if residues are incorporated into the soil (Mhango, Snapp, and Kanyama-Phiri, 2017).

3.4.2 Relevant Research Results

As with all management practices, tradeoffs and set backs will be experienced, however in such a vulnerable setting like SSA where rural farmers depend upon what they grow to survive, it is important that these tradeoffs do not discount benefits seen. With the intercropping of legumes recurrent implications were seen in locations where water constraints were present, the relationship of legumes to inorganic P as a driver for fixation, and the need for additional management techniques to legumes, for full crop requirements to be met.

The application of legume intercropping within water-constrained setting is especially important, as effective nodulation of the legume crop is necessary for the maximization of N fixation, and in the study of Mhango, Snapp, and Kanyama-Phiri (2017) nodule weight was seen to be reduced in seasons where drought was evident. The influence of the crops biophysical setting is also evidenced in the research of Mhango, Snapp, and Kanyama-Phiri (2020) in Malawi, where long-duration pigeon pea crops, which normally should fix more N than that of earlier maturing varieties such as groundnuts, were found to have fixed less N than the compared groundnuts, due to inadequate green water for crop growth. Where rainfall seasons are short, interspecific competition may limit the vegetative growth of pigeon pea and have negative results for BNF (Mhango, Snapp, and Kanyama-Phiri, 2017).

Alongside the integration of legumes, additional management practices may be necessary to maximize the outputs of legume crops. Due to the fact that in some studies legumes in the study were only able to meet the requirement of N for maize crops by 12-50%, leading to the need for additional sources of nutrients (Mhango, Snapp, and Kanyama-Phiri, 2017; 2020). Inorganic P amendments were also seen to be a driver for BNF, therefore intercropped systems should employ some judicious use of P-fertilizer (Mhango, Snapp, and Kanyama-Phiri, 2017). Model-based explorations before and after the implementation of activities were ran to explore potential tradeoffs seen with the intercropping of legumes (Smith et al., 2016; Snapp et al., 2018). Tradeoffs observed with the integration of legumes were an overall increase in operating costs, due to increased labor and seed price (Kerr et al., 2019; Timler et al., 2017). Again, more research is necessary to fully understand these, especially over a longer period of time.

3.4.3 Nutritional Impact of Legumes

For humans, maize-legume mixed systems can increase the resilience of a farm through diversification, as different crops can provide safety nets if one crop is struck by drought, disease, or pests (Smith et al., 2016). Therefore providing the household with back up food sources to sole-maize, and a more diversified diet through legumes that are rich in protein, micronutrients, and fiber (Snapp et al., 2019; Timler et al., 2017). These conclusions are supported by field trials and simulations that look at legume-maize systems, finding that overall nutritional standing of the household and dietary diversity will increase in comparison to sole-maize cropping (Kerr et al., 2019; Snapp et al., 2018). In Malawi, Kerr et al. (2019) found that over a two-year period, intercropping maize with additional crops was associated with increased food security, and the use of organic soil amendments associated with gains in dietary diversity.

3.4.4 Doubled-up Legume Rotation

For ESA, a primary SI technology implemented in Malawi has been that of doubled-up legume rotation (DLR). DLR is an innovative technology where two legumes with complementing phenology are intercropped and grown within rotation of a maize crop (Smith et al., 2016). Most commonly the legumes are a combination of a slow growing pigeon pea crop (5-8 months to reach maturity) and a fast-growing legume such as groundnuts (or soybeans) (that matures around 4 month) as an understory crop to produce N-rich biomass (Smith et al., 2016; Snapp et al., 2019).

Looking at crop performance when legumes are introduced, is an important indicator, as a decrease in yields may signify competition between crops that is not beneficial for intercropping (Snapp et al., 2018). Kerr et al., (2019) found that production/performance varied per site, with legume integration most beneficial at the most marginal sites (Kerr et al., 2019). Looking at the simulations completed by Smith et al., 2016 over 26 growing seasons, DLR systems were found to produce maize yields equivalent to that of sole crop maize (Smith et al., 2016). What is clear is that DLR systems in Malawi have shown comparable grain yields and protein yields in comparison to maize monocrops (Snapp et al., 2010). However in situations where water is limited or fertilizer is applied, results were more varied, and more research is necessary to fully understand the impact (Smith et al., 2016; Snapp et al., 2018). For crop performance one factor is also the increase in environmental performance, as DLR systems have been shown to allow for higher accumulations of soil C and N stocks overtime (Snapp et al., 2018). Therefore crop performance should be projected to increase overtime, as the environmental setting that plants are grown in increases in fertility (Smith et al., 2016; Snapp et al., 2018).

3.4.5 Residue Management

Residue management within DLR is a crucial component to increasing soil fertility benefits of the system (Benzner Kerr et al., 2007). Within Malawi, different regions have been seen to employ different management techniques of residues (Valbuena et al., 2015). Residue application seems to depend upon four elements being: farmers decisions, food production quantitates, access to other biomass sources, and biomass requirements. It has also been observed that smallholder farmers who own livestock are more likely to have extra residue biomass to be put back onto the field (Benzner Kerr et al., 2007).

3.5 Barriers to Sustainable Intensification (SI)

There has been significant research undertaken in SSA and within Malawi on what drives farmers to long-term adoption of SI practices. Often farmers decision to adopt SI management are based on experienced ecosystem service outputs, such as an increase in yields. However with both biophysical and socio-economic conditions influencing farmers decision, a variety of barriers and constraints can be cited for the currently low adoption rates (Jambo et al., 2019; Mhango, Snapp, & Phiri, 2013; Ortega et al., 2016). Most commonly being: farmer perceptions and perceived tradeoffs, market access, and labor requirements (Snapp et al., 2002).

Table 2: Barriers to SI

Source	**Barrier**
Intrinsic	-Perception of legumes (Ortega et al., 2016) -Risk adverse -Dietary preference
Farm	-Temporal periods for returns to be seen -Land size
Economic	-Lack of financial resources (Jambo et al., 2019) -High cost of legume seeds -Market access -Little market for legume sales -Labor constraints (Ortega et al., 2016; Snapp et al., 2002)
Management choices	-Prioritization of other crops
Institutional	-Lack of institutional support (Thornton et al., 2011)

3.6 Identification of Knowledge Gaps

From the review on existing literature, the following knowledge gaps have been identified and are addressed in the proposed research:

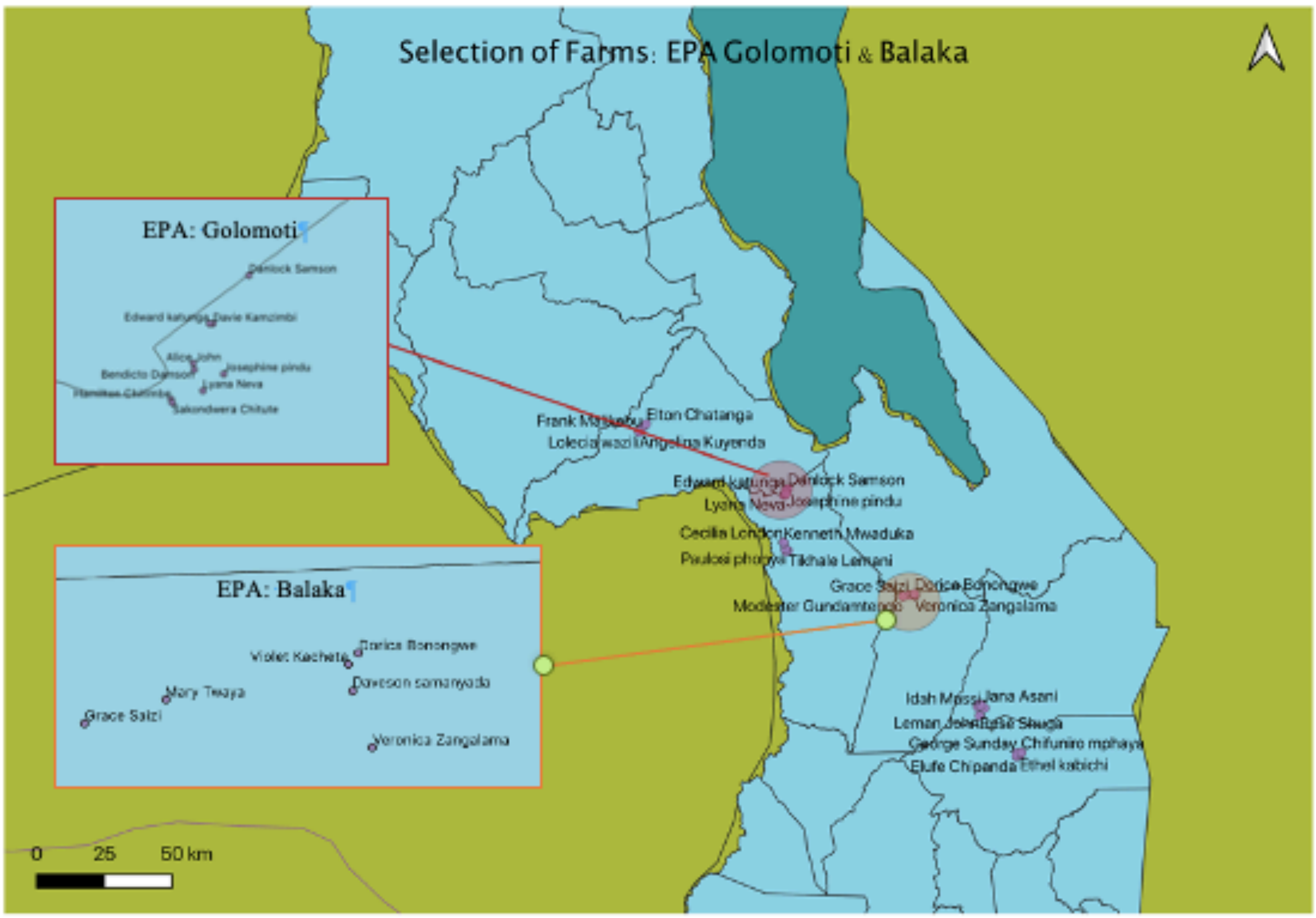
- Diversity of farmers within Central Malawi and how heterogeneity effects SI activities;
- The effects of biologically nitrogen fixing crops at the farm-scale;
- Impact that farm configuration has on SI technology effect and adoption;
- Understanding of climatic variability and its effects on farm configuration and SI technologies; and
- Drivers for SI adoption within different farming groups and zones.

4.0 RESEARCH AREA

The following study was conducted in Central Malawi, over four AfricaRISING selected districts and EPA sites (EPA: Golomoti, Kandeu, Lintipe, Songani, and Balaka). A total of 54 farms were surveyed, and can be seen by name in the below Map (Map 1). **For this research a focus was on EPA Golomoti.** The decision to focus on Golomoti was based on discussions with the AfricaRISING Malawi team, and the results of additional statistical analysis seen in Section 7.0

Participating farmers included three treatment groups defined by the AfricaRISING project: 1) mother trial farmers[1]; 2) baby trial farmers[2]; and 3) control farmers[3]. The map seen below depicts the research location and farmer distribution over Central Malawi, with EPA Golomoti and Balaka highlighted.

Map 1. Distribution of Farms in Central Malawi



[1] Mother-trial farmers are those who have implemented a range of sustainable intensification technologies on their farms, and have high rates of exposure to researchers and extension officers from the Africa RISING ESA project.
[2] Baby-trial farmers are a selected group of farmers associated with a mother trial.
[3] These are farmers that are located within villages that have participated in Africa RISING activities but are farms that have not directly benefited or been exposed to Africa RISING technologies.

4.1 Biophysical Setting of Central Malawi

Central Malawi covers a variety of agro-ecological and climatic zones. This is coupled with location-based differences in population densities and market access (Ortega et al., 2016). A breakdown of potentially influencing biophysical characteristics can be seen in Table 6.

Table 3: Biophysical Characteristics of EPA Sites

Location by EPA	Elevation	Water Availability	Rainfall	Soil	Characterization	Source
Golomoti	**554 m (low)**	**Low with high evapotranspiration**	**-Variable rainfall -Annual mean 834 mm[4] -Seasonal 933 mm[5]**	**Mix of eutric fluvisols and eutric cambisols**	**-Low agriculture potential -Good market access -Low population density**	**Smith, 2014 Smith et al., 2016 Benson, Mabiso, Nankhuni, 2016**
Kandeu	909 m (medium)	Medium	-Annual mean 855 mm -Seasonal 864 mm	Mix of orthic ferralsols and chromic luvisols	-Medium agricultural potential -poor market access -low population density	Smith, 2014 Smith et al., 2016 Benson, Mabiso, Nankhuni, 2016
Lintipe	1236 m (high)	High	-Well distributed rainfall -Annual mean 937 mm -Seasonal 929 mm	Mix of ferric livisols	-High agricultural Potential	Smith, 2014 Smith et al., 2016
Songani	791 m (medium)	N/A	-Annual mean 1,371 mm	Ferruginous, Ferralitic Soils	-Mid-altitude plateau -Poor market access -Low population density	Ngwira et al, 2017 Benson, Mabiso, Nankhuni, 2016
Balaka	Range of 200-500 m (lakeshore and upper shire valley)	N/A	-Annual mean 800 mm	Sand and loamy sand	-Good market access -Low population density	Makate and Mango, 2017 Kamanga, 2011 Benson, Mabiso, Nankhuni, 2016

[4] Mean rainfall from 1979 to 2005
[5] Mean seasonal taken over 2013/2014

5.0 OUTLINE OF MATERIALS & METHODS

This section will outline the materials and methods used during this research, and describe the flow of research through outlined phases.

5.1 Data Set and Tools Employed

- Research was based off of the AfricaRISING MSU survey carried out over the 2019/2020 cropping season. Cleaned survey responses were provided by the AfricaRISING Malawi team.
- A comprehensive literature review was employed of all relevant AfricaRISING documents, related research, and FarmDESIGN related work.
- GIS geo-spatial analysis was carried out to examine farm locations within Central Malawi and provide visualizations of farm distributions.
- R Analysis, was carried out to conduct statistical analysis and visualization of data sets.
- FarmDESIGN was employed to analyze farm-scale indicators.

5.2 Phases of Research

Research was carried out through three phases which are presented in figure one. Each phase is detailed in the following sections.

PHASE 1 Preliminary Analysis: Was completed to determine statistic-based patterns of farms and to create representative farms based on in-field data.

Outlined in Sections:

6.0: Preliminary Analysis
7.0: Results of Analysis
8.0: Transition from Phase One to Phase 2

PHASE 2 Modeling: Allowed for whole farm analysis so farm-scale effects of SI technologies could be assessed.

Outlined in Sections:

9.0: Basis of Model and the Deed process
10.0: Creation of Representative Farms
11.0: FarmDESIGN Inputs

PHASE 3 Final Analysis: Analysis of FarmDESIGN generated results.

Outlined in Sections:

12.0: Final Analysis

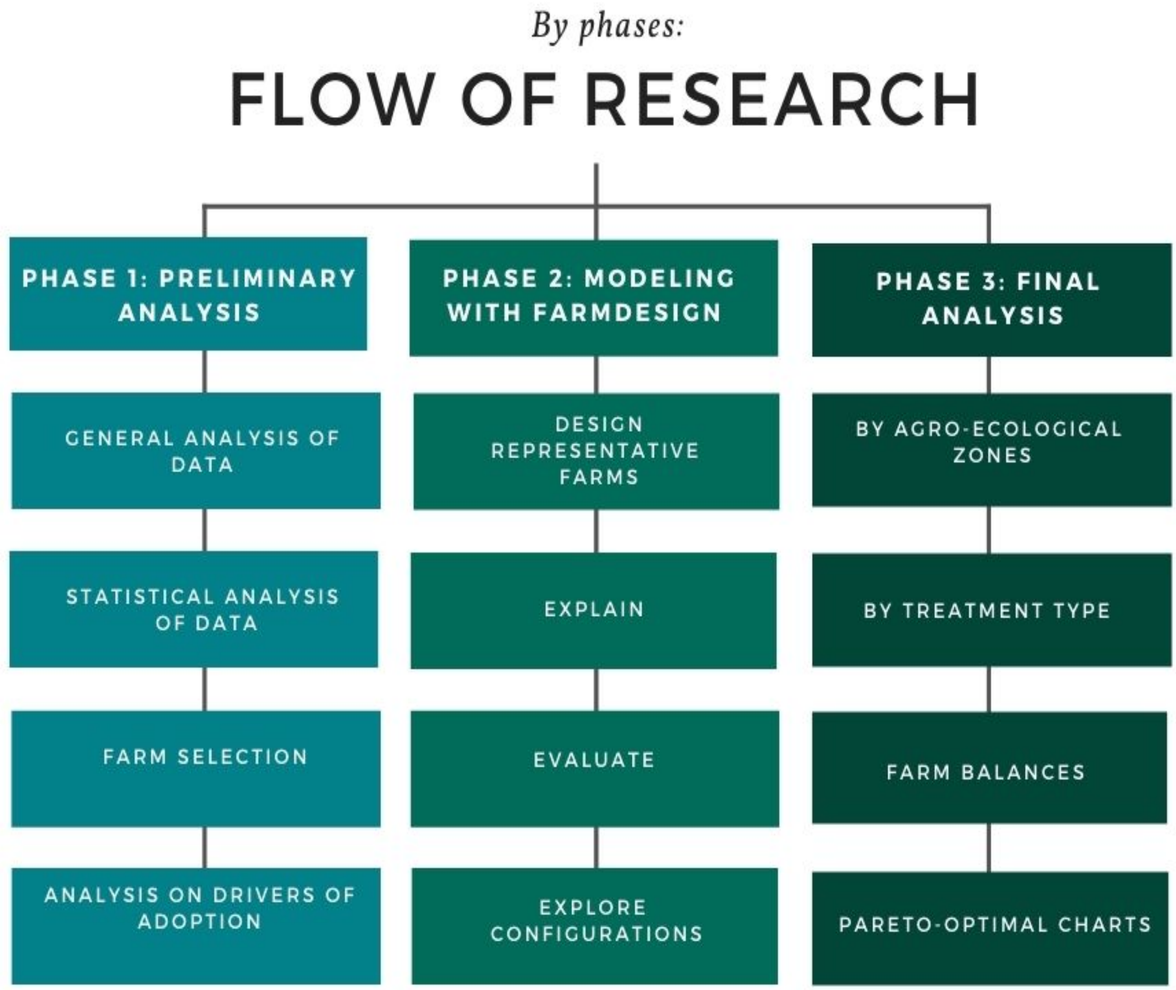


Fig. 1: Breakdown of the Flow of Research

6.0 PHASE 1: PRELIMINARY ANALYSIS

This phase focused on determining the main differences between farmers based on treatment type and location. For analysis to be carried out, a set of decision variables was determined. The variables, justification, and description are outlined below.

6.1 Farmer Heterogeneity & Assumptions

As seen in section 3.1, differences between farmers must be considered when carrying out any level of analysis. For this research, due to the small sample size of farmers surveyed, a farmer typology was not created. Although a typology was not carried out, heterogeneity was explored through other statistical means. This included analysis of farms by treatment type and location over a selection of variables. The variables that were chosen to be assessed were based on literature regarding key themes in what drives (or constrains) a farmer's ability to make decisions regarding his farm. In general this is a farms level of "resource endowment" and a farm's "orientation."

With the use of resource endowment and orientation as guiding points for variables, some assumptions have been made surrounding these terms. As resource endowment and orientation of a farmer can mean many things, in this research resource endowment assumes in line with the research of Timler et al., 2013 that a farmer who has a large area, and cattle, are well endowed. While a farmer with less total cultivated land, and fewer livestock, less endowed. Farmer orientation also followed that of Timler et al., 2013. With the orientation of a farmer based on the type of crops grown on his or her farm. With the assumption that farmers growing cash crops (cotton or tobacco) are more market oriented than a farmer who only grows subsistence crops.

6.1.1 Variables for Analysis

The following variables (Table 5) were chosen, with a brief description and their potential on-farm indicator.

Table 4: Selected Variables for Analysis

Variable:	Description:	Potential Indicator of:
Total items owned	Refers to survey pt. 3: all items marked owned by head of household (such as farm equipment, and other household items i.e. bike, radio, tv)	-Resource endowment
Total NPK applied	Refers to survey pt. 5: and is the sum of all NPK applied per plot in kg/ha within a farm	-Resource endowment -Goals of farmer
Total cultivated land (ha)	Refers to survey pt. 4: total_cultivated_land in ha (can include rented out land)	-Farm size -Resource endowment
Total plots per farm	Refers to survey pt. 5: number of plots per farm	-Indicator of diversity
Number of crops per farm	Refers to survey pt. 4: and is the sum of the total crops farmed per farm	-Indicator of diversity

Total sheep, goats, and cattle owned	Refers to the total sheep and goats owned per farmer (from survey pt. 2: livestock) Cattle were not assessed as only ___ out of the farmers of the far	-Indicator of total livestock -Resource endowment
Total hired hours*	Refers to survey pt. 6: This is the sum of both Male and female labour hours combined per farm	-Indicator of labor -Resource endowment

*Some issues were seen with the labour data which may skew the results of total hired hours.

6.1.2 Hypotheses

Based on project understanding and literature the following hypotheses were made for preliminary data analysis:

1) Some clustering between the 54 farms would be evident in the PCA.
2) Mother farmers would have more crop diversity (indicated by: total number of crops per farm) than that of baby farmers and control farmers. Due to the fact that these farmers are implementing more AfricaRISING SI "trial plots."
3) Less variation between farms would be seen based on EPA, than that of Treatment Type.
4) Resource endowment variables (i.e. total items owned, NPK applied, total cultivated land, and hired hours) would be closely correlated.

7.0 PHASE 1: RESULTS OF PRELIMINARY ANALYSIS

General analysis was carried out over the 54 farms to explore potential patterns, data distributions, clusters, and differences by Treatment Type (i.e. mother, baby, or control farmer) and location seen by EPA. Results are seen as follows: 1) Averages per group, 2) Description of PCA conducted, 3) PCA results 4) Two-way ANOVA tests 5) Regression analysis and 6) Adoption analysis.

7.1 General Characteristics of Farms by Treatment Type and EPA

For a basic understanding of the "average" farm per treatment type, all of the variables seen in Table 4 were assessed with averages and modes when applicable. Results follow:

Table 5: Averages of Selected Variables by Treatment Type

Treatment Type	Total Sheep, Cattle and Goats Owned	Total Items Owned	Total Plots per Farm	Total cultivated land	Number of crops per farm	Total NPK applied	Total hired labor (in hours)
1 (Mother)	3	4	7	0.93	4	123.82	3,090.94
2 (Baby)	3	3	4	0.70	3	98.25	1,876.33
3 (Control)	1	3	3	0.61	2	76.99	735.78

Table 6: Averages of Selected Variables by EPA

EPA	Total Sheep, Cattle and Goats Owned		Total Items Owned		Total Plots per Farm		Total cultivated land	Number of crops per farm (Diversity)		Total NPK applied	Total hired labor (in hours)
	Average	Mode	Average	Mode	Average	Mode		Average	Mode		
1 (Balaka)	3	0	3	4	4	4	0.72	3	4	79.78	3,641.1
2 (Golomoti)	4	6	4	5	7	5	1.08	4	3	136.70	2,295.45
3 (Kandeu)	2	0	3	3	5	5	0.81	3	3	165.73	681.33
4 (Linthipe)	2	0	2	1	5	3	0.68	3	2	74.46	998.6
5 (Songani)	1	0	3	2	4	3	0.57	3	3	78.97	1583.53

7.2 Exploration of PCA In-put

A PCA was conducted to visualize overall farm distribution and clusters of farms based on their similarity against the selected set of variables (justified in Section 6.1, Table 4) and seen in Figure 3. The PCA was completed using R Studio.

Figures 2- 5: Contribution of Variables to PCA

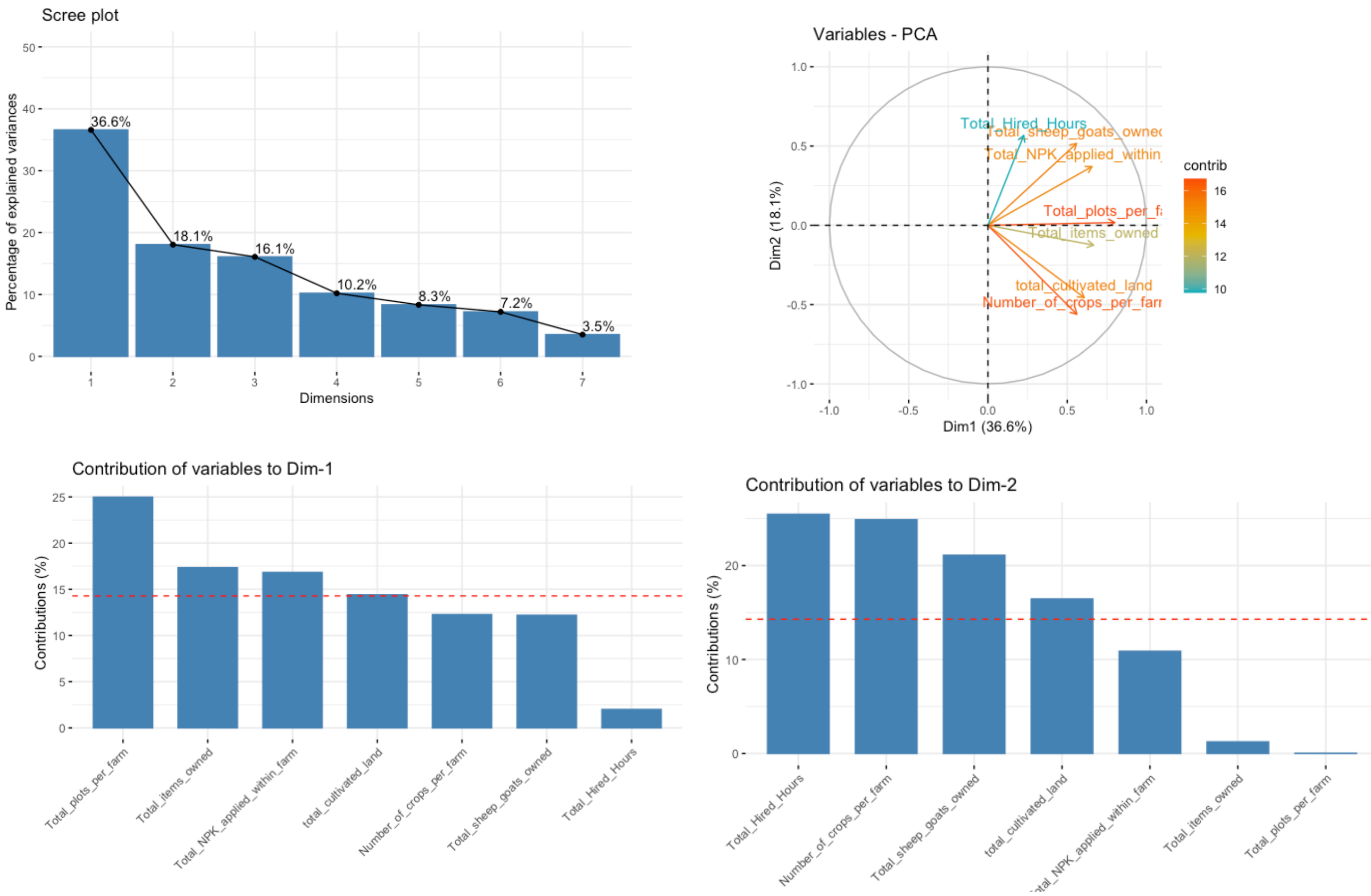


Fig. 2 (top left): Scree plot associated with PCA; **Fig. 3 (top right)** Variables and their contribution to both dimensions; **Fig. 4 (bottom left)** Contribution of variables to dimension 1; **Fig. 5 (bottom right)** Contribution of variables to dimension 2.

Looking at the figures above it is important to note the variables that drive the biggest variation between farms. Figure two shows that 54.7% of the variance is explained by the first two dimensions, with dimension 1 and 2 further visualized in figure 4 and 5. In figure 4 and 5, one can see that the following variables account for over 20% of variation within a dimension being: total plots per farm, total hired hours, number of crops per farm, and total livestock. With the combined influence on both dimensions seen in Figure 3. Following this a deeper analysis can be carried out on the level of significance that these variables have and what drives this, being either EPA or Treatment type.

7.3 By Treatment Type

There are clear differences between treatment type, seen by the groupings which are presented in Fig. 6. With the biggest variation coming between Host farmer and the Control group.

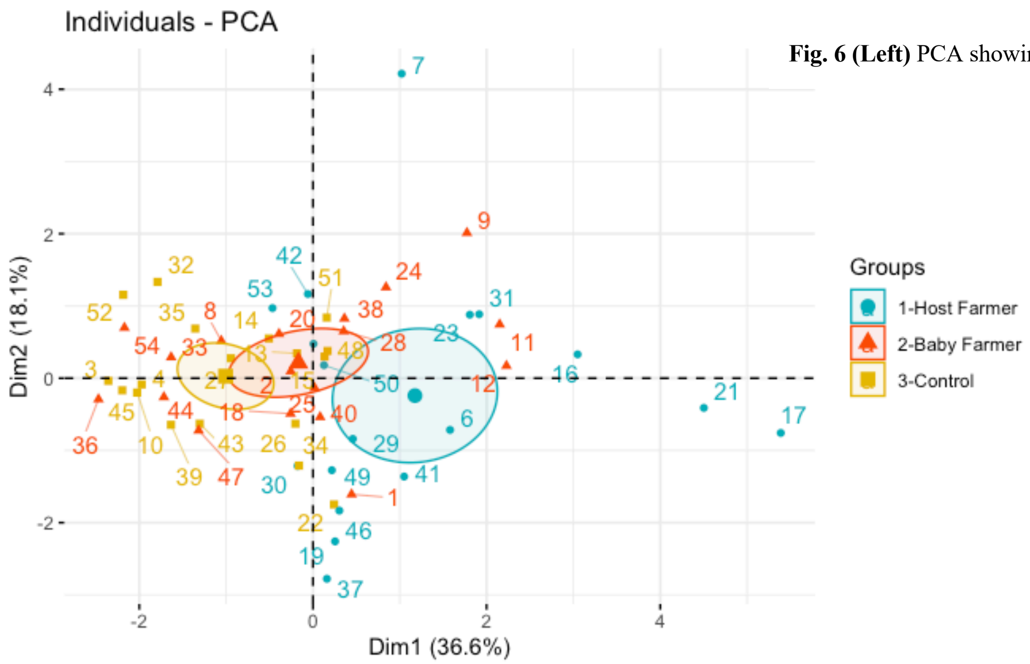
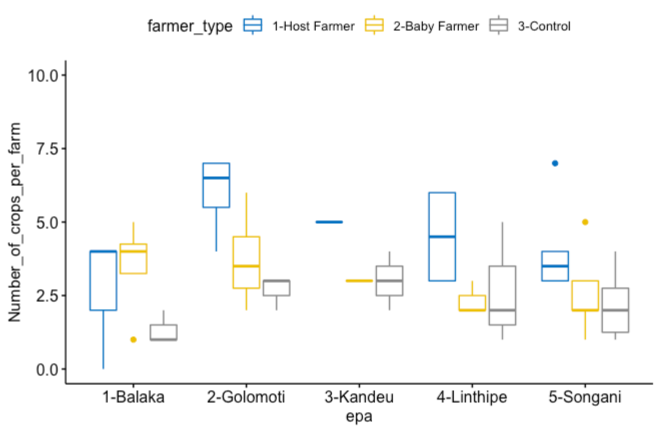


Fig. 6 (Left) PCA showing treatment type groupings

Conclusions from the PCA, are also supported by a two-way ANOVA test, which shows that crops per farm have a statistically significant P value (0.000668) between treatment type (normality of data assumed based on shapiro-wilk normality test results of: W = 0.98958, p-value = 0.9188).



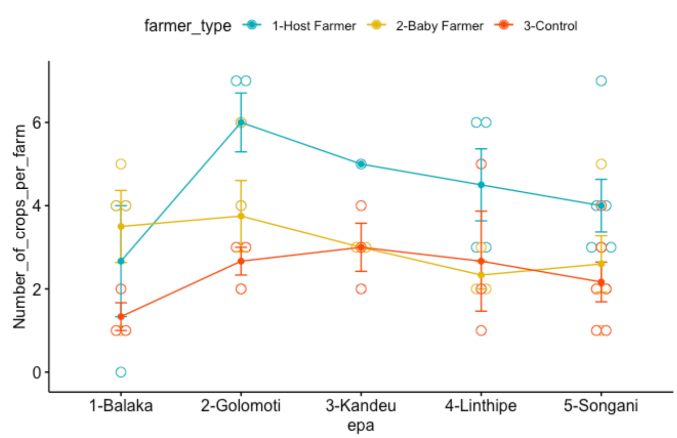
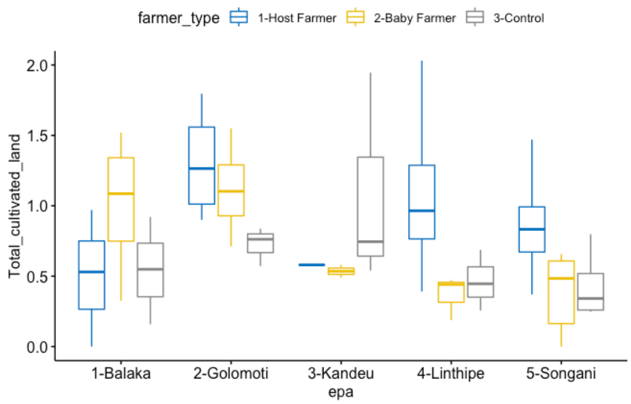


Fig. 7 (Left) ANOVA for Number of Crops Per Farm; **Fig. 8 (Right)** Further Analysis of Distribution

Additional analysis was carried out on the relationship between Treatment Type and hired labour, livestock on farm, and items owned. However results of these were not significant.

7.4 By EPA Site

Additional differences between EPA can be seen visualized with a two-way ANOVA test seen in Figure 9. Where the p value for EPA is significant, meaning that EPA is associated with significant differences in total_cultivated_land. Points fall along reference line we can assume normality, conclusion supported by shapiro-wilk normality test (results: W = 0.98007, p-value = 0.5032).



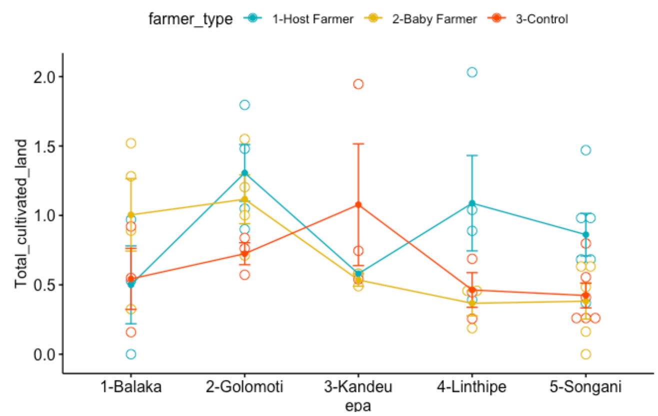


Fig. 9 (Left) ANOVA for Total Cultivated Land; **Fig 10 (Right)** Further Analysis of Distribution

Analysis was also carried out by EPA site. By looking at farms and differences that arise based on location, some conclusions can be made on the influence of the agro-ecological zones that farms are nested within. Differences between EPA sites are evident, visualized by the distribution of sites over a PCA. Although clusters overlap, variation can be seen based on the variables used[6]. The largest between Golomoti and Balaka (group 1 and 2), which cluster furthest apart on the PCA.

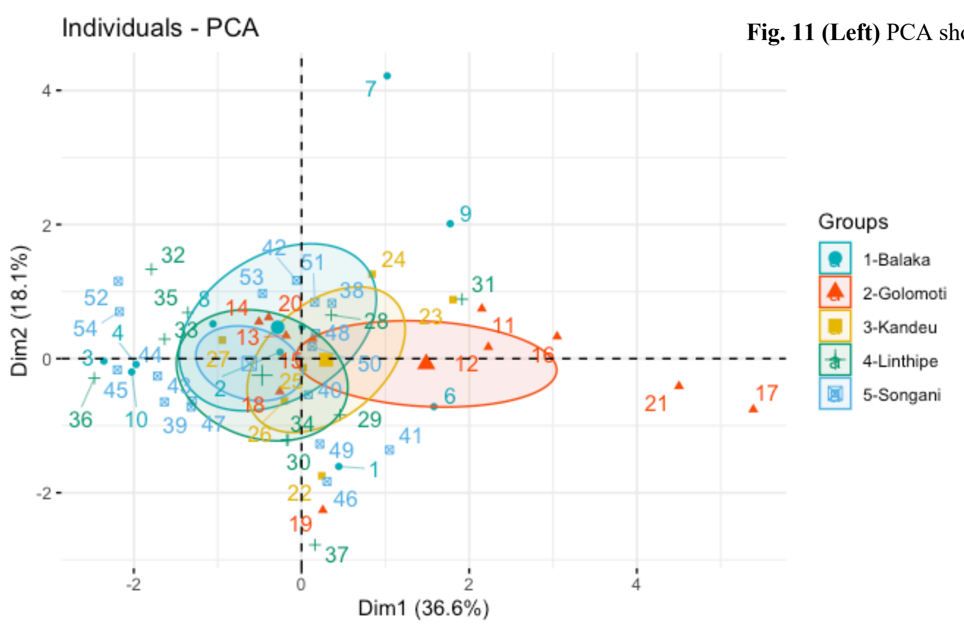


Fig. 11 (Left) PCA showing EPA groupings

[6] Variables are stated in Table 4 and are the same for both PCAs visualized in Figure 6 and Figure 11

Differences by location were also seen in soil and number of crops being farmed, visualized in Figure 12 and Figure 13. With Figure 12 showing farmer reported soil types within each EPA, where it can be shown that Balaka has significantly less diverse soil, than the other four EPA sites. In figure 13, diversity of crops grown in each EPA is shown. Clearly Maize (the yellow pie slice) predominates all locations, which is in-line with literature. Again, Balaka can be seen to have lower crop diversity than the other sites with Golomoti having the highest number of crop variations grown.

Fig. 12 Soil percentages documented per EPA, with legend in the bottom right

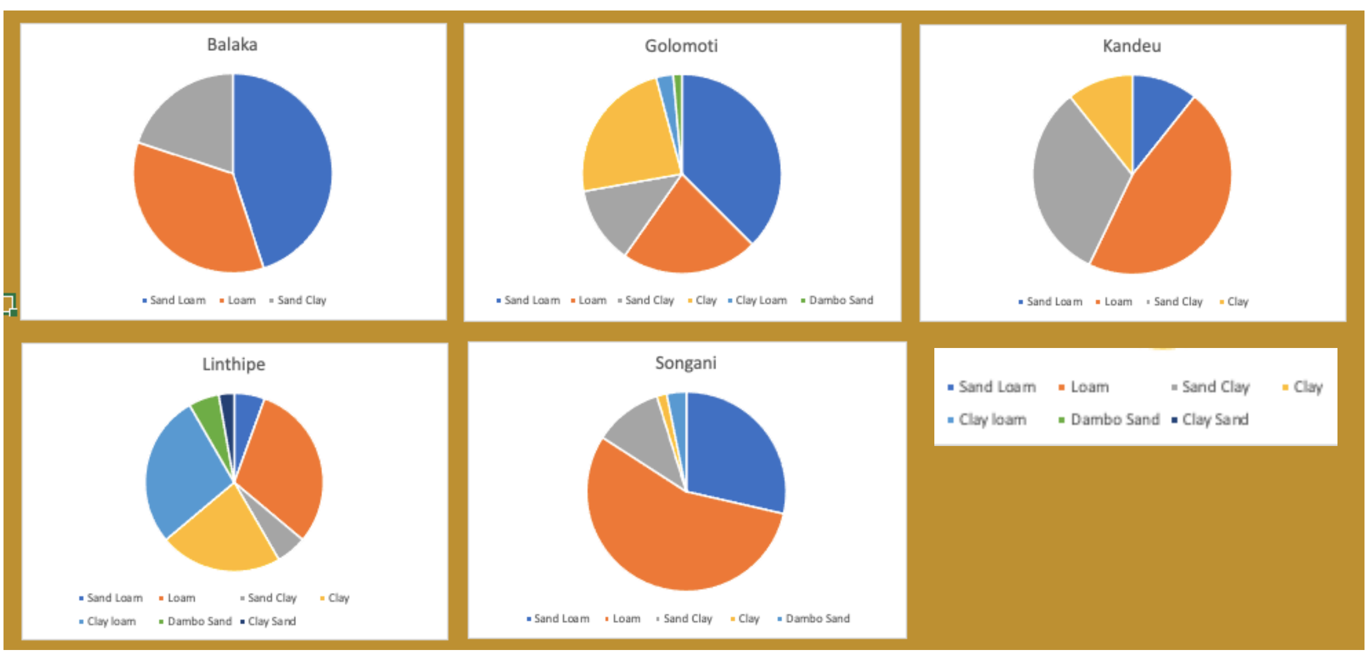


Fig. 13 Percentages of crops farmed per EPA

7.5 Linear Regression

The following linear regressions were carried out, to check the relationship of variables hypothesized to be correlated. Results of these regressions follow:

The number of crops per farm was seen as a significant influence of variation in the PCA when looking at differences between treatment type and EPA. This is supported by Fig. 15 showing a clear trend of mother farmers having more crops than baby or control farmers. This also influences total cultivated land, with the more crops on a farm leading to a slight correlation to more cultivated area.

It was hypothesized that variables acting as indicators for resource endowment would be closely correlated. That farms with more total items owned would also have a greater total cultivated land. However, this was not found to be significantly correlated. In addition NPK application was also hypothesized to be correlated to total cultivated land, however there was no significant correlation.

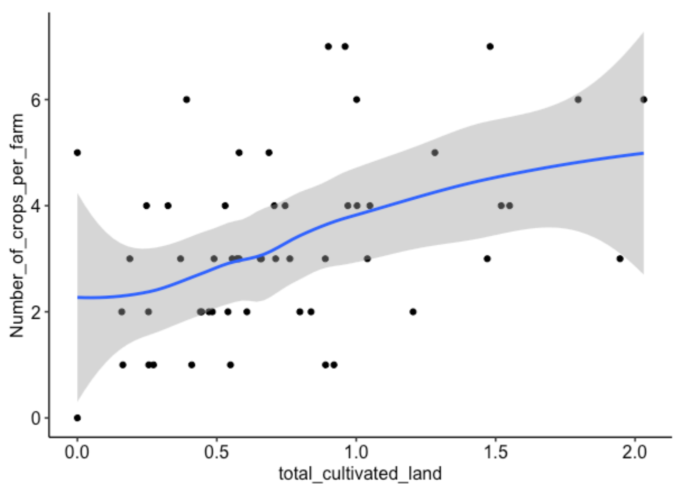


Fig. 14 Relation of crops per farm to total cultivated land

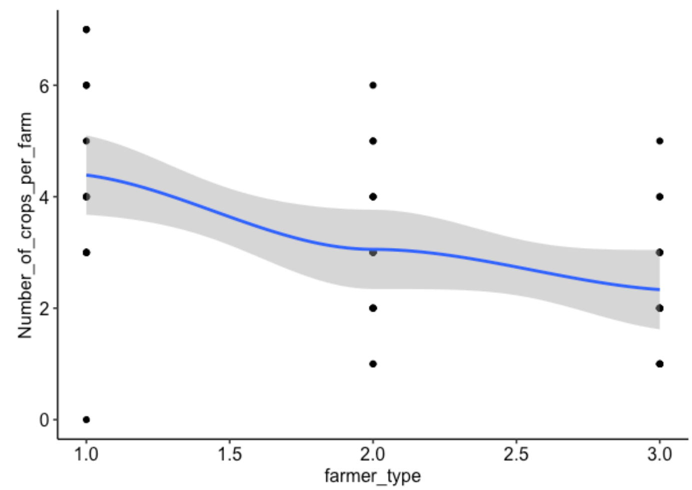


Fig. 15 Relation of crops per farm to farmer type (mother farmer as 1, baby as 2, and control as 3)

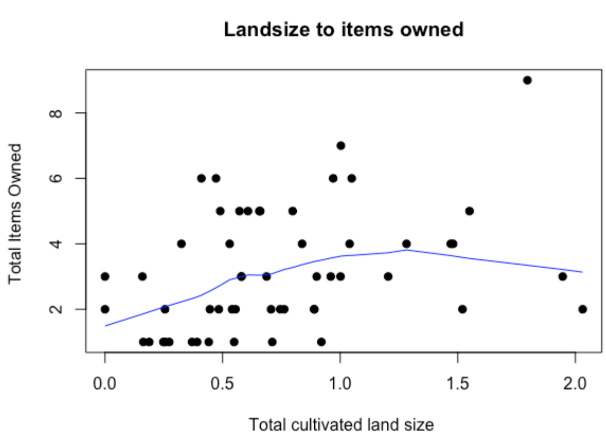


Fig. 16 Total items owned in relation to total cultivated land

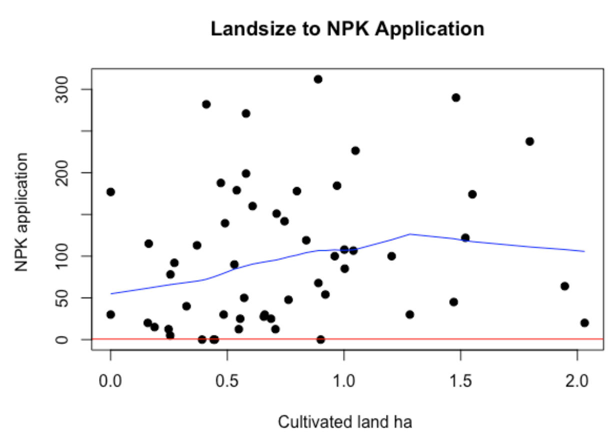


Fig. 17 Rates of NPK applied to total cultivated land

7.6 Adoption Analysis[7]

For the adoption of SI activities, analysis was carried out over most commonly adopted activities or not adopted, and reasons why. In addition statistical analyses were carried out over survey responses to understand the connection of response to EPA and treatment type.

Farmers were most likely to adopt drought tolerant crop varieties, with 91% of all surveyed farmers choosing to adopt this SI technology. This was closely followed by maize-legume intercropping at 89%. However, more farmers were more likely to quit the use of drought tolerant crop varieties than those that adopted maize-legume intercropping. With eight farmers stopping the use of drought tolerant varieties due to seed availability, and six farmers stopping the introduction of maize-legume intercropping on their farms because of "expected productivity relative to conventional practices." A breakdown of top activities farmers chose to adopt follows:

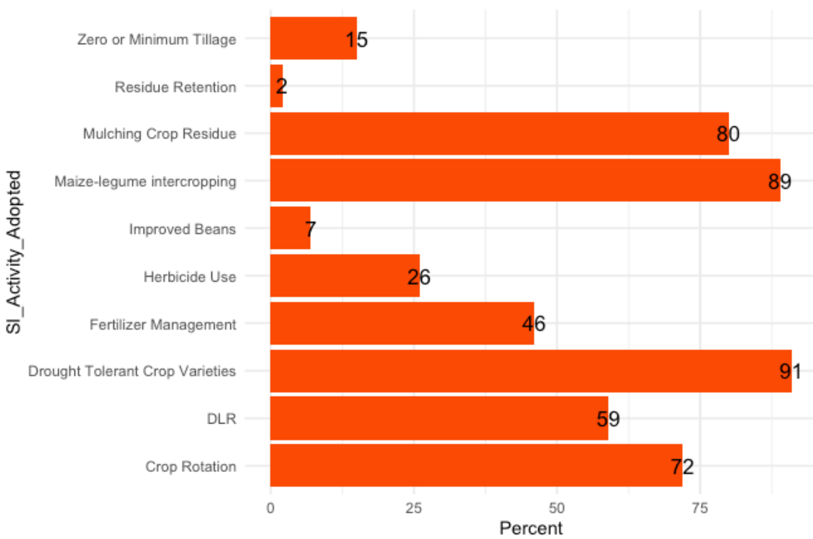


Fig. 18 Percent of SI Activities Adopted by a Farmer

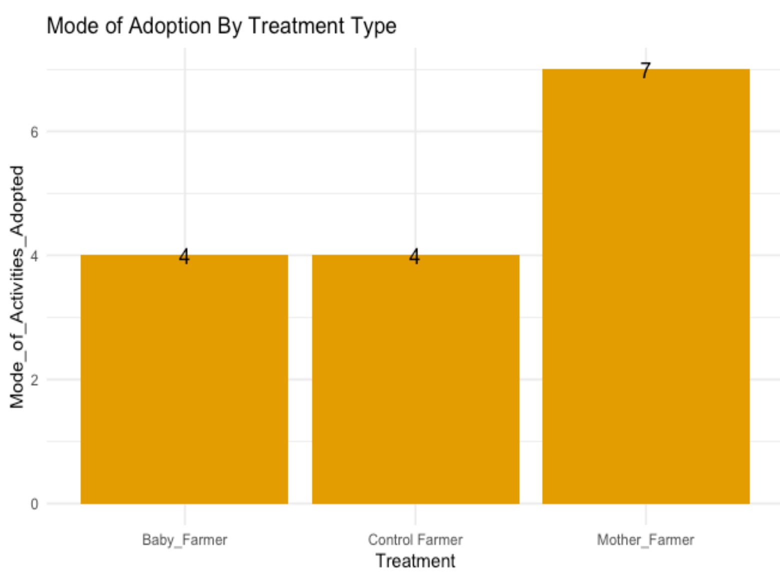


Fig. 19 Mode of Activities Adopted per Treatment

[7] Annex 2: Full analysis of adoption responses can be seen here.

Top reasons cited for adoption:

- Increasing yields

*Top activities farmers choose **not** to adopt:*

- DLR (39%)
- Fertilizer management (22%)

*Top reasons cited for **not** adopting:*

- Seed/herbicide availability
- Confidence or uncertainty of the production benefits

It is seen that mother farmers are more likely to adopt SI technologies within their farm with the mode of activities adopted per treatment type (Fig. 19). This is supported by project documents as the treatment "mother" farmers have been with the project longer, and have adopted more technologies (IITA, 2017).

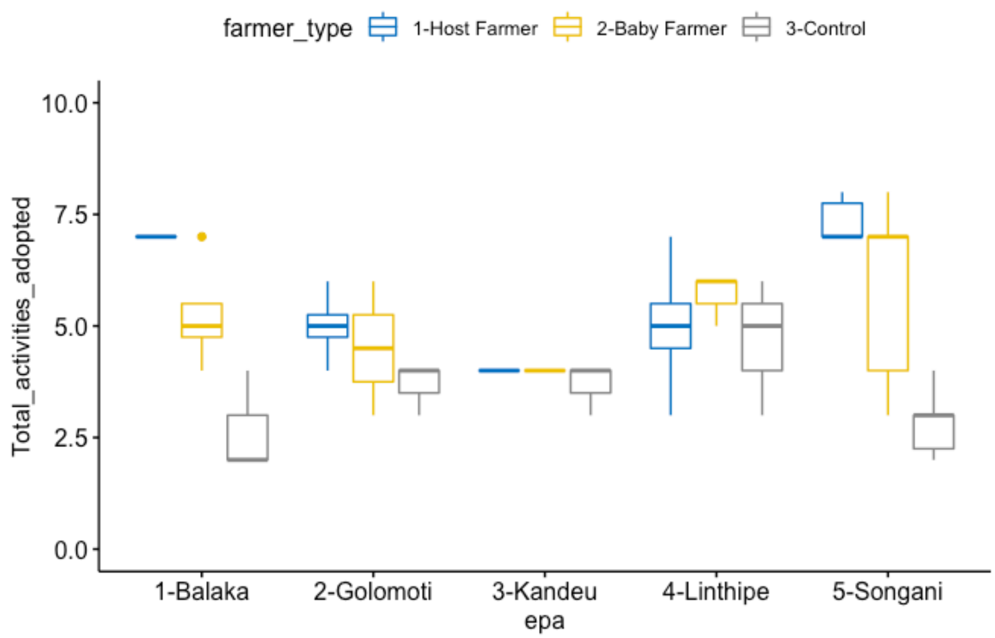


Fig. 20 Total Activities Adopted per Treatment

	Df	Sum Sq	Mean Sq	F value	Pr (>F)
EPA	4	12.10	3.03	2.267	0.07937
Farmer Type	2	63.27	31.64	23.705	1.83e-07***
Epa: Farmer Type	8	32.67	4.08	3.060	0.00902**
Residuals	39	52.05	1.33		

8.0 TRANSITION: PHASE ONE TO PHASE TWO

A preliminary analysis was carried out in Phase One to understand the potential statistical differences in farms by treatment type and location so that a selection of farms could be modeled further in Phase Two. **Based on the analysis it was determined to focus on the EPA site Golomoti and to further model a Mother and Baby Farmer.**

8.1 Overall Trends by Treatment Type

It can be concluded from the preliminary analysis that there are differences between the 54 farmers reviewed in Central Malawi, with significant differences based on both treatment type and location. This is in-line with research and findings in (section 3.1), where levels of heterogeneity are commonly seen between smallholder farmers even within close geospatial proximity and small data sets (Giller et al. 2011; Zingore et al., 2008; Tittonell et al., 2005).

Variation between Treatment Type point to differing levels of "resource endowment," with Mother Farmers having statistically significant higher levels of resource endowment. This conclusion is based on the assumption that resource endowment is defined by the variables: total items owned, total NPK applied, total cultivated land, and total hired labour. Mother Farmers were also seen to have higher levels of crop diversity (indicator: crops per farm), seen in general averages and the linear regression carried out in (Fig. 15), which was positively correlated as a determinant of more hectares of land cultivated.

Treatment type also corresponds to number of SI activities adopted, with mother trial farmers having adopted more SI activities than that of baby trial farmers. This is to be expected, as mother trial farmers have had longer exposure to AfricaRISING activities and support from the project to adopt more trial plots on their farm (IITA, 2017).

8.2 Overall Trends by EPA

By location (or EPA), clustering based on EPA can be seen, with the largest variation existing between Golomoti from the other EPA sites (Fig. 11). Golomoti's variation is most explained by dimension 1 within the PCA, with higher levels of plots per farm, items owned, NPK applied, and total cultivated land (Fig. 4 PCA dimension 1 variables). Therefore it can also be concluded to have higher levels of resource endowment than that of the other EPA sites. Biophysically, Golomoti also has the most reported soil diversity and crop diversity between the different EPAs. It was interesting to find the EPA site with the largest difference from other EPAs to also have the highest levels of soil diversity and crop diversity.

8.3 General Takeaway

In Phase Two a Mother and Baby Farmer will be created to represent each type and to model further farm-scale interactions. These farms will represent the general trends found in the initial analysis.

9.0 PHASE 2: MODELING IN FARMDESIGN

Due to the complex and dynamic nature of farming systems, an integrated approach must be adopted. This allows for analysis of the farm, so that the effects of SI technologies on a farms environmental, social, nutritional, and economic standing can be understood holistically (Estrada-Carmona et al., 2019; Groot et al., 2012). Therefore a bio-economic model, FarmDESIGN was used to conduct a holistic analysis of selected farm systems. This will allow for household and field level metrics to be upscaled and for modeling to take place that can integrate all of the changes seen within the farm, so farm-scale impacts can be analyzed.

FarmDESIGN was designed for the application of mixed-crop livestock farm systems, to quantify the performance of the whole farm system by assessing performance indicators of system components being: environmental performance, social aspects, household nutrition, and economic standing (Estrada-Carmona et al., 2019; Groot et al., 2012). FarmDESIGN can model different farms and their flow of resources (cash, labor, and food) between the farm, the household, and outside the farm system to the market (Ditzler et al., 2019). This can provide an understanding of the overall "stock" a farm may have after SI technologies were implemented, or in control farms where SI technologies were not.
A visualization of this can be seen in Figure 1. Resource balances for all four categories (environmental, social, nutrition, and economics) seen in Table 6 will be calculated by the model and serve as proxy indicators for the impacts of SI technologies.

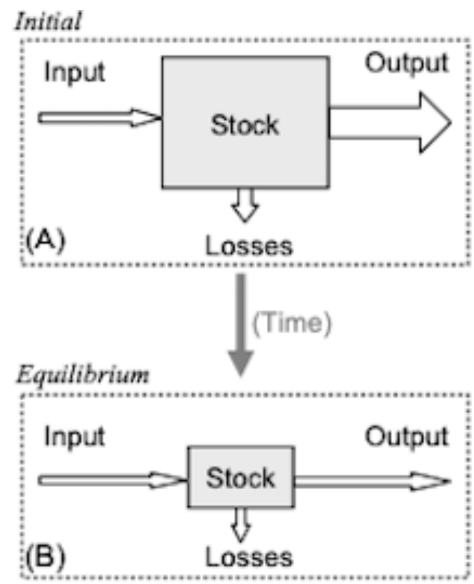


Fig. 21 Input-Output Flow

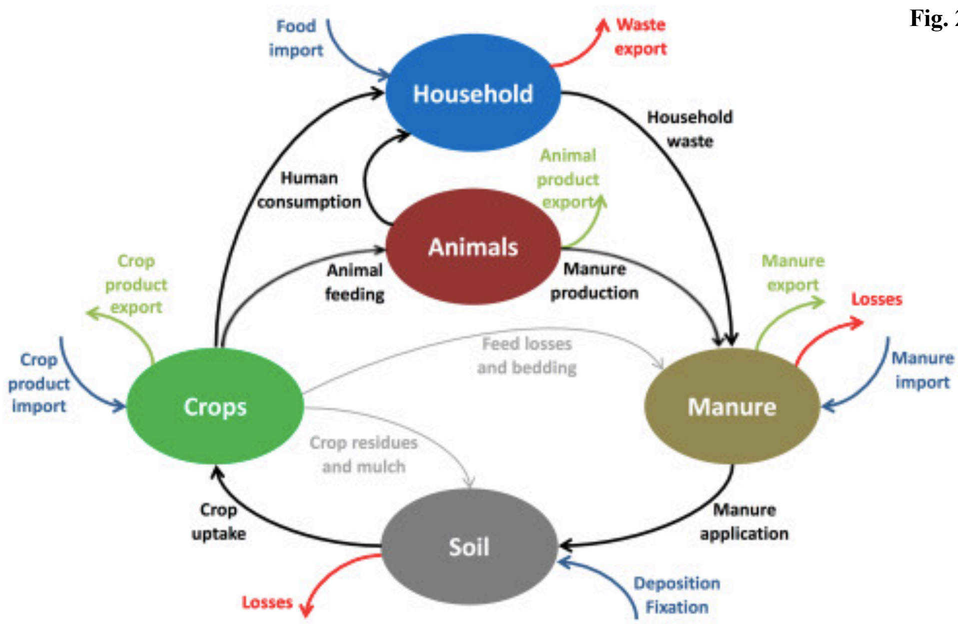


Fig. 22 Schematic representation of the FarmDESIGN model showing farm resource Flows: with black and grey arrows representing resource flows within the farm-household; blue arrows inflows; and green outflows; red losses (figure from Ditzler et al., 2019)

The potential flows of resources are visualized in Figure 2, within components of soil, crops, manure, animals, and household.

9.1 The DEED Process

In order to configure the model to represent to the selected farms, a 4-step model-based scientific procedure was followed: *Describe, Explain, Explore and (re)Design* (DEED) (Giller et al., 2008; Groot and Oomen 2016). The DEED process for FarmDESIGN introduces an additional step: evaluate. These processes will be used to configure each farm.

For the *describe* step, the focus was on accurately creating a representative farm for each treatment type in Golomoti. To do this, averages of farmer response were taken to understand a basic idea of farm configurations and to set a minimum framework to follow. From here, a selection of crops, animals, and farm size was made for each modeled farm in Golomoti. During the *explain* step, an overview of the outcomes of the current farm configurations was reviewed, and a selection of decision variables and objectives were made for each farm depending on the treatment type.

Once the data was set in FarmDESIGN, the *evaluate* step took place. Where model calculated outcomes and balances could be analyzed. In Table 28, key indicators of the four social-ecological categories within a farm can be seen, and in Table 29, the farm balances used to assess at the farm-scale. For detailed calculations of these indicators, please refer to the study of Groot et al. (2012). Finally the *explore* step took place to explore alternative farm configurations based on model generated solutions. This focused on exploring difference scenarios to understand potential tradeoffs, synergies, and impact of SI activities on the different treatment types.

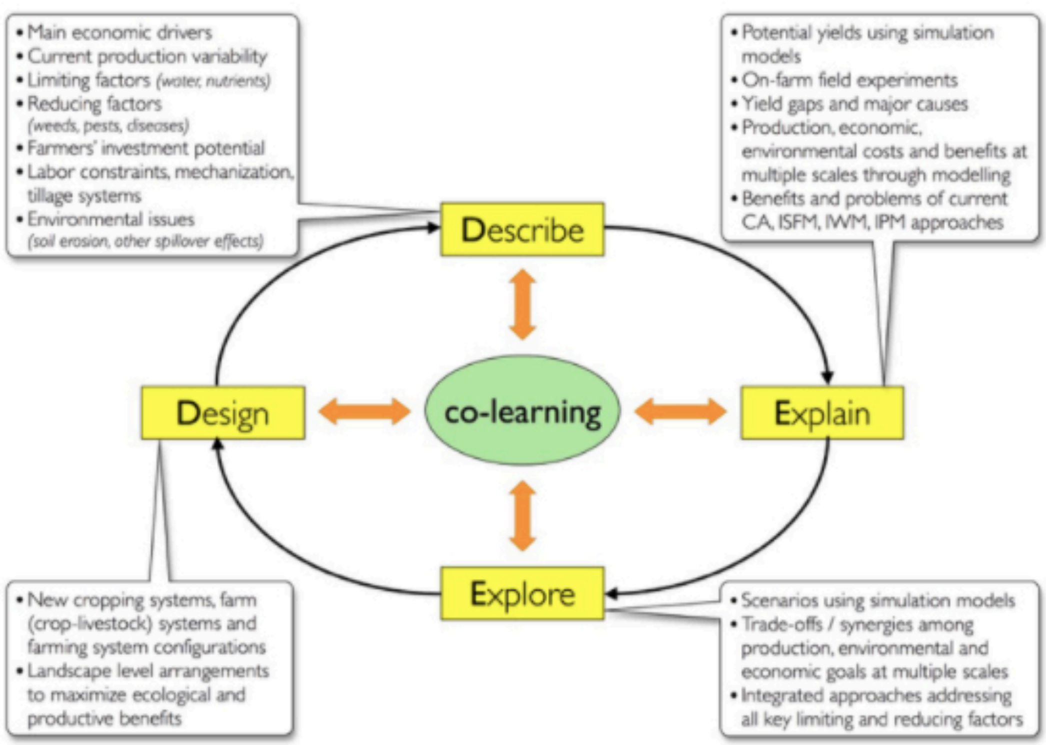


Fig. 23 The DEED Process (Jager, Giller, and Brouwer, 2018)

10.0 CREATION OF REPRESENTATIVE FARMS

In this phase, two representative farms were created for each treatment type, a Mother and a Baby farmer for the EPA Golomoti. These farms differ in characteristics such as land size, crops, household, and livestock, therefore configuration was based on calculated data averages. First a qualitative description of each farmer was made, followed by the process of quantitatively building the farm.

10.1 Qualitative Description of Modeled Farms

The following farms are fictional, but based in data and statistically representative of Golomoti and the farmers Treatment Type.

10.1.1 FARM 1: Golomoti, Mother Trial Farmer

This farmer is 45 married and living with their spouse with a family of 4. He has been farming in Golomoti for his entire life currently cultivating 1.306 hectares of land, a larger piece than most farmers. He has completed 6 years of education and his wife and himself work full time on the farm, with additional help from children or short term hired labour if necessary. His son is 18, and works off the farm when work is available, his daughter is 22 and pregnant, doing minimal work on the farm. He farms to sustain his family, but also is more market oriented than some, by farming cotton to sell. With higher levels of owned land and farm equipment, livestock, and a cash crop, we can assume this farmer has higher level of resource endowment and is more market oriented.

As a mother trial farmer, he has been with the AfricaRISING project longer, and has introduced more “trial plots” of SI activities on his land, including three cropping configurations that involve the introduction of legumes on to his farm.

His main goal is to remain resilient to the recent droughts experienced, and increase profits.

10.1.2 FARM 2: Golomoti, Baby Trial Farmer

This farmer is female, 38, widowed, and the head of household for a family of 5. She works full time on the farm, with additional help from her four children. Farming a total of 1.1 hectares with few livestock, and no cash crops we can assume she is a subsistence farmer of lower resource endowment with less market orientation.

As a baby trial farmer, she has been recently working with a mother farmer to introduce more SI activities on to her farm. This can be seen in the adoption of a maize-legume intercropping.

Her main goal is to remain food secure, and eventually have the resources to sell more of her crops and to gain a cash crop like cotton or tobacco.

10.2 Visual of Golomoti

The following images were taken previously during field work during the research of Timler et al., 2013. They serve as a basis for understanding the general terrain and setting of the above farms.

Images taken by Carl Timler in Golomoti, Malawi 2013

A quantitative description of the two modeled farms follows. First with an explanation of the Golomoti Mother Trial Farmer, and Second with the Baby Farmer.

10.3 Quantitative Description of Golomoti, Mother Trial Farmer

Within Golomoti, a total of four Mother trial farmers were surveyed. Table 7 shows averages taken of these four farmers to set a baseline idea for farm configuration.

Table 7: Averages for Golomoti Mother Trial Farmers

Household Members	Total land cultivated	Plots	# of Crops	Goats	Chickens	Pigs	Total NPK	Fertilizer Application	Crop Residue	Manure
4	1.306	11	6	5	6	1	217.65 kg	Most commonly: -Maize/bean intercrops -Maize	Usually applied	No manure or FYM applied

Following a general analysis of averages, a more detailed look at crops, percent of crops per total farm, and fertilizer application per crop was taken. Table 8 shows a breakdown of this. Due to discrepancies seen within the survey responses a new farm was created to adjust for discrepancies, seen in the darker (right) column for each farmer. Discrepancies were seen between survey responses for part four and part five, regarding crops, plot number, and size of farm. The following shows all four mother farmers in Golomoti:

Table 8: Breakdown of Crop Averages Golomoti Mother Trial Farmers

Farmer: Danlock Samson

SURVEY RESPONSE Pt. 4		SURVEY Pt. 5		CONFIGURED FROM BOTH Pt. 4 & Pt. 5		
CROP	PLOT SIZE (ha)	CROP	PLOT SIZE (ha)	CROP	PLOT SIZE (ha)	PERCENT OF LAND
Maize	0.546	Maize and groundnuts	0.228	Maize	0.546	36%
Groundnut	0.014	Maize and cowpea	0.261	Maize and groundnuts	0.228	15%
Maize and groundnut	0.228	groundnuts	0.014	Maize and cowpea	0.261	17%
Maize and pigeonpea	0.261	Cotton_5	0.431	groundnuts	0.014	1%
		Groundnuts (trial)	0.0025	Cotton_5	0.431	28%
		Cowpea (trial)	0.002	Groundnuts (trial)	0.0025	0%
		Pegion pea and groundnuts (trial	0.003	Cowpea (trial)	0.002	0%
		Maize (trial)	0.0025	Pegion pea and groundnuts (trial)	0.003	0%
		Soyabean (trial)	0.025	Soyabean (trial)	0.025	2%
		Maize unfertilized (trial)	0.002	Maize unfertilized (trial)	0.002	0%
		Maize and pegion peas (trial)	0.0025	Maize and pegion peas (trial)	0.0025	0%
		Soya bean and pegion pea (trial)	0.0025	Soya bean and pegion pea (trial)	0.0025	0%
Total cultivated land (ha):	**1.049**		**0.976**		**1.5195**	**100%**

Farmer: Bendicto Damson

SURVEY RESPONSE Pt. 4		SURVEY Pt. 5		CONFIGURED FROM BOTH Pt. 4 & Pt. 5		
CROP	PLOT SIZE (ha)	CROP	PLOT SIZE (ha)	CROP	PLOT SIZE (ha)	PERCENT OF LAND
Maize	0.029	Maize and pegion pea (trial)	0.003	Maize and pegion pea	0.003	0%
Soybean	0.023	Cow pea and pegion pea (trial)	0.008	Cow pea and pegion pea	0.008	1%
Cowpea	0.008	Cow pea (trial)	0.008	Cow pea (trial)	0.008	1%
Maize and groudnut	0.008	Maize (fertilized)	0.029	Maize (fertilized)	0.029	3%
Maize and pigeonpea	0.003	Maize (unfertlized)	0.015	Maize (unfertilized)	0.015	1%
Doubled up legumes	0.024	Cotton	0.486	Cotton	0.486	43%
		Maize and cow pea	0.593	Maize and cow pea	0.593	52%
Total cultivated land (ha):	**0.095**		**1.142**		**1.142**	**100%**

Farmer: Paulsoi Phonya						
SURVEY RESPONSE Pt. 4		**SURVEY Pt. 5**		**CONFIGURED FROM BOTH Pt. 4 & Pt. 5**		
CROP	PLOT SIZE (ha)	CROP	PLOT SIZE (ha)	CROP	PLOT SIZE (ha)	PERCENT OF LAND
Groundnut	0.04	Maize	0.18	Maize	0.2	19%
Soybean	0.022	Maize and beans	0.56	Maize (fertilized)	0.06	6%
Cowpea	0.02	Groundnuts	0.04	Maize/beans	0.56	53%
Maize groundnut	0.04	Maize and groundnuts	0.04	Maize/groundnuts	0.04	4%
Maize pigeonpea	0.02	Groundnuts (trial)	0.02	Maize/pigeonpea	0.02	2%
Doubled up legumes	0.01	Maize and pegion pea	0.02	Maize/cow pea	0.04	4%
		Soya bean	0.06	Groundnuts	0.02	2%
		Maize (fertilized)	0.06	Soyabean	0.06	6%
		Maize and cow pea	0.04	Cowpea	0.02	2%
		Cowpea	0.02	Doubled up legumes	0.04	4%
		Pegion pea and groundnuts	0.04			
		Maize	0.02			
Total cultivated land (ha):	**0.152**		**1.1**		**1.06**	**100%**

Farmer: Josephine Pindu						
SURVEY RESPONSE Pt. 4		**SURVEY Pt. 5**		**CONFIGURED FROM BOTH Pt. 4 & Pt. 5**		
CROP	PLOT SIZE (ha)	CROP	PLOT SIZE (ha)	CROP	PLOT SIZE (ha)	PERCENT OF LAND
Maize	0.412	Maize (trial)	0.076	Maize	0.412	72%
Groudnut	0.054	Soyabean (trial)	0.01	Groudnut	0.054	9%
Soybean	0.01	Groundnuts (trial)	0.008	Soybean	0.01	2%
Cowpea	0.008	Cowpeas (trial)	0.008	Cowpea	0.008	1%
Maize and soybean	0.074	Groundnuts and pigeon pea (trial	0.008	Maize/soy	0.074	13%
Maize and pigeon pea	0.008	Maize pigeon pea (trial)	0.008	Maize/pp	0.008	1%
Doubled up legumes	0.008			Doubled up	0.008	1%
Total cultivated land (ha):	**0.574**		**0.118**		**0.574**	**100%**

Based off of Table 7, and Table 8, a final farm was created to represent Mother farmers in Golomoti (seen in Table 9). This farm served as the basis for what was modeled in FarmDESIGN.

Table 9: Golomoti, Mother Trial Farmer Configuration

FARM CHARACTERISTICS		**ANIMALS**		**HYPOTHETICAL FARM**		**FERTILIZER**	
						NPK	**UREA**
Household members:	4	Goats	4	**Main crops**			
Total cultivated land	1.31 ha	Chickens	6	Maize (fertilized)	0.38	50	50
Total plots	10	Pigs	1	Maize / cowpea	0.32	87.72	87.72
				Cash crop (Cotton)	0.45		
				Trial plots			
				Maize (trial: unfertilized)	0.03		
				Maize / pigeonpea	0.008	37.5	37.5
				Maize / groundnut	0.04	37.5	37.5
				Groundnut / pigeon pea (doubled up)	0.015	20	20
				Groundnut	0.03		
				Soybean	0.03		
				Cowpea	0.009		
				TOTAL CULTIVATED LAND	**1.31**		
				TOTAL PLOTS	**10**	**232.72**	**232.72**

Here the basic farm characteristics are seen, with total animals on the farm (goats, chickens, and pigs) and the crops grown within the farm. The main crops grown are maize, maize and cowpea, and cotton. Trial plots are unfertilized maize, maize and pigeonpea, maize and groundnut, cowpea and pigeonpea, groundnut, soybean, and cowpea. Fertilizer is applied to maize and maize legume intercrops.

10.4 Quantitative Description of Golomoti, Baby Trial Farmer

The above process was completed again for baby trial farmers in Golomoti. A total of four Baby trial farmers were surveyed. Table 10 shows averages taken of these four farmers to set a baseline idea for farm configuration.

Table 10: Averages for Golomoti Baby Trial Farmers

Household Members	Total land cultivated	Plots	# of Crops	Goats	Chickens	Ducks	Total NPK	Fertilizer Application	Crop Residue	Manure
5	1.11	5	4	4	4	3	133 kg	Most commonly: -Maize/bean intercrops -Maize	Usually applied	Some manure or FYM applied

Table 11: Breakdown of Crop Averages Golomoti Baby Trial Farmers

Farmer: Alice John

SURVEY RESPONSE Pt. 4		SURVEY Pt. 5		CONFIGURED FROM BOTH Pt. 4 & Pt. 5		
CROP	PLOT SIZE (ha)	CROP	PLOT SIZE (ha)	CROP	PLOT SIZE (ha)	PERCENT OF LAND
Maize	0.412	Groundnut	0.022	Maize	0.412	41%
Groundnut	0.022	Cotton	0.106	Groundnut	0.022	2%
Tobacco	0.106	Cabbages	0.003	Cotton	0.106	11%
Cabbages	0.003	Millet	0.017	Cabbages	0.003	0%
Other cereal	0.017	Maize and Cowpea	0.44	Millet	0.017	2%
Maize and Pigeonpea	0.44			Maize and Cowpea	0.44	44%
Total cultivated land (ha):	**1**		**0.588**		**1**	**100%**

Farmer: Davie Kamzimbi

SURVEY RESPONSE Pt. 4		SURVEY Pt. 5		CONFIGURED FROM BOTH Pt. 4 & Pt. 5		
CROP	PLOT SIZE (ha)	CROP	PLOT SIZE (ha)	CROP	PLOT SIZE (ha)	PERCENT OF LAND
Maize	0.12	Maize	0.12	Maize	0.12	8%
Groundnut	0.09	Groundnut	0.09	Groundnut	0.09	6%
Tobacco	0.5	Tobacco	0.5	Cotton	0.5	32%
Maize and pigeonpea	0.84	Maize and Cowpea	0.84	Maize and cowpea	0.84	54%
Total cultivated land (ha):	**1.55**		**1.55**		**1.55**	**100%**

Farmer: Edward Katunga

SURVEY RESPONSE Pt. 4		SURVEY Pt. 5		CONFIGURED FROM BOTH Pt. 4 & Pt. 5		
CROP	PLOT SIZE (ha)	CROP	PLOT SIZE (ha)	CROP	PLOT SIZE (ha)	PERCENT OF LAND
Maize	0.99	Maize	0.99	Maize	0.99	82%
Groundnut	0.22	Groundnut	0.22	Groundnut	0.22	18%
Total cultivated land (ha):	**1.21**		**1.21**		**1.21**	**100%**

Farmer: Tikhale Lemani

SURVEY RESPONSE Pt. 4		SURVEY Pt. 5		CONFIGURED FROM BOTH Pt. 4 & Pt. 5		
CROP	PLOT SIZE (ha)	CROP	PLOT SIZE (ha)	CROP	PLOT SIZE (ha)	PERCENT OF LAND
Maize	0.7	Maize	0.7	Maize	0.7	98%
Groudnut	0.006	Groundnut	0.006	Groudnut	0.006	1%
Soybean	0.005	Soybean	0.005	Soybean	0.005	1%
Total cultivated land (ha):	**0.711**		**0.711**		**0.711**	**100%**

Based off of Table 10, and Table 11, a final farm was created to represent Baby Farmers in Golomoti (seen in Table 12). This farm served as the basis for what was modeled in FarmDESIGN.

Table 12: Golomoti, Baby Trial Farmer Configuration

FARM CHARACTERISTICS		ANIMALS		HYPOTHETICAL FARM		FERTILIZER	
Household members:	5	Goats	4	**Main crops**		**NPK**	**UREA**
Total cultivated land	1.11 ha	Chickens	4	Maize	0.41	53.55	53.55
Total plots	4	Ducks	3				
				Trial plots			
				Maize and Pigeonpea	0.47	67.02	67.02
				Groundnut	0.22		
				Soybean	0.005		
				TOTAL CULTIVATED LAND	**1.11**		
				TOTAL PLOTS	**4**	**120.57**	**120.57**

11.0 INPUTS FOR FARMDESIGN

The required inputs for FarmDESIGN will come from the household survey over the 2019/2020 cropping season and when necessary literature will be used to supplement survey responses. Inputs into FarmDESIGN are categorized by the following categories:

- **11.1 Environmental Data**
- **11.2 Labour Inputs**
- **11.3 Crop Yields**
- **11.4 Livestock and Animal Parameters**
- **11.5 Economic Parameters**
- **11.6 Product Destination & Human Nutrition Module**

11.1 Environmental Parameters

For this research the focus was on EPA Golomoti, within the District of Dedza. Therefore the model was parameterized for this environmental setting.

The environmental research of Timler et al., 2013 in the district of Dedza was used to provide inputs for the necessary environmental parameters. This data is the averaged result of soil testing over 12 farms in Dedza and Ntcheu districts (Timler et al., 2013). In general it was found that soil organic matter varied considerably between farms, that pH was low, and strongly correlated to the contents of nitrogen, phosphorus, and potassium. On general low levels of nutrient content in the soil was found (Timler et al., 2013). The environmental parameters in FarmDESIGN used are as follows:

Table 13: Environmental Parameters Used in the FarmDESIGN Model

Environment	Parameter	Value
Soil	Soil Type	Sand
	Active Organic Matter (%)	1.22
	Organic Matter Degradation (%/year)	2
	Soil depth (m)	0.2
	Soil Bulk Density (Kg/m3)	1450
	Texture factor	1.2
	Non-symbiotic N fixation rate (Kg ha^{-1} $year^{-1}$)	5
Climate	Nitrogen deposition (kg/ha/year)	5
	Phosphorus deposition (kg/ha/year)	1
	Potassium deposition (kg/ha/year)	10
	Mean temperature (C)	24
	pF<3.5 (days)	155
	Water available (m3/year)	0
Erosion	Soil eroded (mm)	0
	OM content in erosion (%)	0
	N content in erosion (%)	0
	P content in erosion (%)	0
	K content in erosion (%)	0

11.2 Labour Inputs

For labour inputs, due to data discrepancies too large to overlook in the 2019/2020 survey, labour data was supplemented by previous labour research in Malawi and sub-Saharan Africa. Problems with labour data sets are common, and even within research surrounding labour, large discrepancies are seen (Rusinamhodzi, 2012). This is due to the irregular nature that farming activities are carried out and difficulties of accurately estimating time spent for cropping work (Rusinamhodzi, 2012).

To get a basic understanding of labour, a typical cropping calendar for Malawi was made. Within Malawi there are two predominate seasons, the dry season, which lasts between May and October, where little to no farming is done (Silberg et al., 2017). Followed by a unimodal rainy season which begins in November and continues to April (Silberg et al., 2017). Historically the "first rains" acted as a signal for farmers to begin planting (Vizy et al., 2006). However it is important to note that changes in rainfall and extended dry periods have resulted in uncertainty as to when to plant, with some farmers beginning earlier than November (Vizy et al., 2006). The cropping calendar used for this research assumes that farmers begin sowing in November, but in an extremely variable year of rainfall this may not be accurate.

A typical year for a farmer in Malawi follows:

October: Land preparation
November: Sowing
December: Sowing and fertilizer application
January: Weeding
February: Weeding
March: Harvesting
April: Harvesting
May: Harvesting, threshing, and residue incorporation
June: Continued harvest and related tasks such as storage and shelling, residue incorporation
July: Less cropping related work
August: Less cropping related work
September: Less cropping related work

11.2.1 Assumptions Made for Labour

To get a general idea of labour demands the above calendar was used. At minimum it was assumed that for 9 months, two people are working for 40 hours a week, with four weeks a month, for a total of 320 hours. Yearly this comes out to 2,880 required man hours for a farm to function. **Typically labour requirements are counted in units of man days per hectare. Therefore days have been used as the main unit of measurement, with the assumption that one day is 6 hours of work. The following assumptions were also made:**

- **Cropping calendar:** For this research it was assumed that the growing season began in November and carried through April where harvesting would begin through June depending on crops planted.

- **Hours of work per day:** For farmer days, farmers can start as early as 4:00 am in their fields during peak periods, but also have periods of little work. With such variation it is difficult to measure time. Therefore a "day" was assumed to consist of an average of **6 hours in total.**
- **Cropping Activities:** Labour in regards to crops typically refer to land preparation, sowing, fertilizer application, weeding, harvesting, and threshing.
- **Intercropping systems would increase planting, fertilizing and weeding time.**
- **Harvest included:** harvest, deshelling, and storage time for crops.
- **Assumed that groundnuts were deshelled:** However, groundnuts do not have to be dehulled but it is a common practice with their selling price increasing if so (Komarek et al., 2018).

11.2.2 Labour by Crop

As this research is focused on the potential impact that SI technologies can have for farmers, one of the main activities being the incorporation of legumes within maize or doubled up legume crops. It was important to understand the labour dynamics per crop. A break down was therefore done, based by crop, and informed by literature from; Franke et al., 2010; and Frank et al., 2014; Oijem et al., 2014.

In general it has been shown that the incorporation of legumes within maize systems in sub-Saharan Africa can lead to an increase in labour requirements over that of sole crops (Kermah, et al., 2017; Komarek, et al., 2018; Mucheru-Muna et al., 2010; Ortega et al., 2016; Ravensbergen, 2018). This is largely due to increased time in planting, weeding, and harvesting in planting configurations that include two or more crops (Mucheru-Muna et al., 2010). Some research indicates the potential of weed suppression in maize-legume intercropping due to more crop biomass and soil cover (Chamango, 2001 and Banik et al., 2006), however the assumption in this research is that there will be an increase in weeding and harvesting time with intercropping configurations. Labour also increased in fertilizer application and weeding days within intercropping system. This is supported by literature in similar systems, where increases in weeding days for intercrop systems were found. Seen in Mozambique with a study of intercropping legumes with maize (Rusinamhodzi, 2012) and in Malawi with an average increase of 36% in weeding time with the intercropping of maize and pigeonpea (Komarek et al., 2018).

Some differentiation can be seen between crops, with soybean having a higher planting time than others due to its dense planting space (Ojiem, 2014). For harvest, an increase in time can be seen especially for groundnuts, due to the labor-intensive process of uprooting groundnuts and then dehulling them (Franke et al., 2010; Komarek et al., 2018).

Table 14: Labour Requirements Per Sole Crop

Activity	**Sole Crops**							**Unit**	**Source**
	Cotton	Maize	Maize (unfertilized)	Pigeonpea	Cowpea	Groundnut	Soybean	Per ha	
Land Cultivation	50	50	50	50	50	50	54	Days	Ojiem et al., 2014
Planting	12	10	10	12	12	11	17	Days	Franke et al., 2010

Fertilizer	0	9	0	0	0	0	0	Days	Ojiem et al., 2014
Weeding 1	25	25	25	36	36	36	36	Days	Franke et al., 2010
Weeding 2	21	21	21	30	30	30	30	Days	83% of the first weeding
Weeding 3	14	14	14	16	16	16	16	Days	Ojiem et al., 2014
Harvest	13	12	12	14	14	34	34	Days	Franke et al., 2010
Threshing	23	23	23	17	17	46	46	Days	Franke et al., 2010
Totals Days per Crop	**158**	**164**	**155**	**175**	**175**	**223**	**233**	**Days**	
Total Hours per Crop	**949**	**984**	**930**	**1,050**	**1,050**	**1,338**	**1,398**	**Hours**	

For the labour days of intercropping systems, Table 14 was used as the foundation, and following the method of Kermah et al., 2017, labour days were estimated for intercrop configurations. Intercrop labour for two crops was the sum of 50% of the sole crop labour, with the time for planting, fertilizing and weeding calculated as 68% of the respective sole crops. This was based on the assumption that these activities would require 18% more labour in an intercrop configuration (Kermah et al., 2017 and Rusinamhodzi et al., 2012). For the intercropping of three crops, labour for the three crops was the sum of 33% of the sole crop labour, with the time for planting, fertilizing, and weeding calculated as 48% of the respective sole crops. This again was based on the assumptions of Kermah et al., 2017 that these activities would require 18% more labour time. For both Tables, the total days and hours per crop were cross checked with alternative estimates to ensure days were inline (including Franke et al., 2014).

Table 15: Labour Requirements Per Intercrop[8]

Activity	**Intercrop**				**Unit**
	Pigeonpea / Maize fertilized	Cowpea / Maize fertilized	Maize / Groundnut / Pigeonpea (DLR)	Doubled up legumes (Pigeonpea / Groundnut)	Days per ha
Land Cultivation	50	50	50	50	Days
Planting	15	15	22	15	Days
Fertilizer	6	6	3	0	Days
Weeding 1	41	41	65	48	Days
Weeding 2	35	35	54	40	Days
Weeding 3	20	20	32	22	Days

[8] Calculations done in excel and provided in Annex 2

Harvest	13	13	20	24	Days
Threshing	20	20	29	32	Days
Totals Days per Intercrop	**200**	**200**	**222**	**231**	**Days**
Total hours[9] per intercrop	**1,200**	**1,200**	**1,332**	**1,386**	**Hours**

[9] Calculation for hours is based on a 6-hour work day

11.3 Crop Yields

Crop yields were originally apart of the AfricaRISING MSU survey carried out over the 2019/2020 cropping season. However, due to in-field problems during the harvest collection, the data regarding crop yields for the 2019/2020 cropping season was unable to be used in this research. Therefore, crop yields were based on a comprehensive literature review to provide verified yield data for Central Malawi.

In Table 17, results of this literature review are seen, with grain yields and biomass yields per sole crop and intercrop. The majority of yield data was based on model simulations created for this region, with APSIM, an innovative crop simulation model parameterized for Central Malawi (Smith et al., 2016). All results were also verified against data from experimental testing trials in Malawi done by Smith et al., 2016 and Kamanga et al., 2010 and research carried out by Timler et al., 2013 in Dedza.

As fertilizer application can be an important variable in crop yields, the fertilizer applied per crop and configuration was what was inputted into FarmDESIGN. With the fertilizer averages of Table 9 and 12, not followed. However, total fertilizer applied based on Smith et al., 2016, was still in line with the total average of fertilizer used in Golomoti (seen in Table 8).

11.3.1 Assumptions Made for Yields

- **Accuracy of literature:** Yields were largely based on the research of Smith et al., 2016 done through model simulations with the model APSIM, verified and calibrated for Golomoti.
- **Yields:** It is assumed that yields are reported as fresh yield, and have inputted directly into FarmDESIGN as "fresh yield."
- **Fertilizer:** Fertilizer followed the research of Smith et al., 2016 and applied rates in connection to their simulated yields.
- **Crop residues:** Are based on literature derived yields and HI.
- **HI:** A set number was used for the HI of each crop, sole, or within a configuration. The goal was to find a representative number closest to the location or to the intercropping configuration. It is assumed that the HI in Table 13 is adequate for this research.

11.3.2 Crop Residue

Crop residue was calculated as the left-over crop residue after grain yields were subtracted. A harvest index was used that corresponded with each crop. Harvest index refers to the balance between weight of the stalk and weight of the grain. Grain yields can be seen in Table 17, and were used in combination with the HI for each crop in Table 16.

$$\text{Crop Residue} = (\text{Total Grain Yield} / \text{HI}) - \text{Total Grain Yield}$$

For inputs of this equation:

- HI (Harvest Index) = Table 16, and the source for each crop
- Total Grain Yield= Table 17, Grain yield for each crop and configuration with source.

Table 16: Harvest Index Used for Crop Residue Calculations

Crop	Harvest Index (HI)	Source, Location
Maize	0.46	Carr MSc Thesis (Malawi)
Cotton	0.41	Waghmare et al., 2018 (India)
Maize / cowpea	0.48 (Maize) / 0.73 (Cowpea)	Thapa (Nepal)
Maize / Pigeonpea	0.48 (Maize) / 0.20 (Pigeonpea)	Smith et al., 2016 (Malawi)
Maize / Groundnut / Pigeonpea	0.48 (Maize) / 0.35 (Groundnut) / 0.20 (Pigeonpea)	Smith et al., 2016 (Malawi)
Groundnut / Pigeonpa	0.35 (Groundnut) / 0.20 (Pigeonpea)	Smith et al., 2016 (Malawi)
Groundnut	0.35	Smith et al., 2016 (Malawi)
Soybean	0.32	Thapa MSc Thesis (Nepal)
Cowpea	0.83	Thapa MSc Thesis (Nepal)

Table 17: Yield Per Crop in Kg/ha[10]

Crops	Grain Yield (Kg/ha)[1]	Residue Yield (Kg/ha)	NPK Applied	Urea Applied	Source, location
Maize (fertilized)	4,000	4,695	69	69	Smith et al., 2016 (Golomoti, Malawi)
Maize (unfertilized)	600	704.35	0	0	Smith et al., 2016 (Golomoti, Malawi)
Cotton	1,208	1,738.34	0	0	Cotton Sector in Malawi (Malawi)
Maize i/c. Cowpea	2,100 (Maize) 1,000 (Cowpea)	2,465.22 (Maize) 204.82 (Cowpea)	69	69	Smith 2014 (Golomoti, Malawi)
Maize i/c. Pigeonpea	3,900 (Maize) 640 (Pigeonpea)	4,578.26 (Maize) 2,560 (Pigeonpea)	69	69	Smith et al., 2016 (Golomoti, Malawi) Africa Rising, 2016 (Dedza, Malawi)
Maize / Groundnut i/c. Pigeonpea (DLR System)	3,100 (Maize) 900 (Groundnut) 640 (Pigeonpea)	3,639.13 (Maize) 1,671.43 (Groundnut) 2,560 (Pigeonpea)	35	35	Smith et al., 2016 (Golomoti, Malawi)
Groundnut i/c. Pigeonpea (Doubled up Legumes)	1,330 (Groundnut) 640 (Pigeonpea)	2,470 (Groundnut) 2,560 (Pigeonpea)	0	0	Africa Rising, 2016 (Dedza, Malawi)
Groundnut	1,650	3,064.29	0	0	Africa Rising, 2016 (Dedza, Malawi)
Soybean*	1,500	3187.50	0	0	Smith et al., 2016 (Golomoti, Malawi)
Cowpea	1,100	225.30	0	0	Smith 2014 (Golomoti, Malawi)

[10] Full calculations for crop residue are provided in Annex 3

11.4 Livestock and Animal Parameters

For the livestock and animals within the Golomoti Mother and Baby farm, animal numbers were based on averages from Table 7 and 10.

In Central Malawi, livestock levels are generally low, and free ranging in communal grasslands, sleeping in sheds at night (Banda et al., 2000).

The following assumptions informed the parameters regarding these animals:

11.4.1 Assumptions Made for Animals

- **Grazing period:** For each animal a set grazing period was made. For ease of feeding, one period was created called "grazing" where animals were fed. Here animals are either grazing on farm or on communal grasslands and sleeping for 9 hours in closed sheds.
- **Grazing period was the same for all animals:** Assumed that chickens, ducks, goats, and pigs all followed the same grazing patterns.
- **Replacement:** Due to low inputs for animals and low animal numbers it is assumed that reproduction of animals is not taking place.
- **Feed for animals:** Was assumed that only crop residue would be fed to livestock.
- **Bedding requirements for animals:** Was assumed to be 0.
- **Animal production:** Rates of production were based on USDA data.
- **Product nutrient content:** Data was based on USDA data for animals (USDA_Data_for_FarmDesign).
- **Minimal labour is spent on animal management.**

11.4.2 Nutritional Content of Feed for Animals

The nutritional content of the feed was based off on feed saturation, feed structure, and energy contents as Metabolizable Energy (ME) and protein contents as Crude Protein (CP) (from feedpedia data set).

Table 18: Nutrient Content of Feed Available for Animals (feedpedia)

Crop	Product	Saturation	Structure	Metabolizable Energy (ME)	Crude Protein (CP)
Cotton*	Residue	N/A	N/A	N/A	148
Cowpea	Residue: Hay	1	3.26	7.8	252
Maize	Residue: Stover	1	4.24	7.6	37
Groundnut	Residue	1	1.12	6.5	112
Pigeonpea	Residue: Forage	1	1.9	9.6	190
Soybean	Residue	1	1.9	7.4	71

*Cotton residue was not included as it is toxic for animal consumption

11.5 Economic Parameters

For the economic parameters, such as input costs, prices of labour, and all products, the currency used was the Malawian Kwatcha (MWK), with an interest rate of 25 percent a year.

11.5.1 Assumptions Made for Economic Parameters

- **Land Costs:** Were set at 30,000 MWK per hectare.
- **Cultivation Costs:** For each crop "cultivation cost" came from the AfricaRISING research in Tanzania on July 2020. Therefore it is assumed that these rates are similar to that of Malawi.
- **Cultivation Costs of Maize-legume intercropping:** Were assumed to be the same and were based off of maize-pigeonpea data.
- **Labour Costs:** Regular, hired, and off-farm labour were all set to be 7 MWK per hour.

11.5.2 Cultivation Costs

Cultivation costs were calculated from that of AfricaRISING research in Tanzania with the exception of cotton costs. Cultivation costs refer to storage costs, seeds, clearing land, and ridge making.

Table 19: Cultivation Costs per Crop

Crop	Cultivation Cost (per Ha/in MWK)	Source, Location
Maize	71,502.05	Tanzania, 2020
Cotton	326,492.02	Southern Africa, 2020
Maize / cowpea	62,877.27	Tanzania, 2020
Maize / Pigeonpea	62,877.27	Tanzania, 2020
Maize / Groundnut / Pigeonpea	62,877.27	Tanzania, 2020
Groundnut / Pigeonpea	66,241.97	Tanzania, 2020
Groundnut	69,606.66	Tanzania, 2020
Soybean	112,500.00	Tanzania, 2020
Cowpea	356.00	Tanzania, 2020

11.5.3 Crop and Animal Product Prices

For the price of crop and animal products, data was taken from available sources seen in Table 19.

Table 20: Crop and Animal Production Prices

Product	Price (per kg/in MWK)	Source
Animal Product		
Eggs	1,300.00	Selina Wamucii Malawi, 2018
Poultry Meat	821.87	Selina Wamucii Malawi, 2018
Goat Milk	718.00	Selina Wamucii, Malawi 2018
Crop Product		
Maize	199.00 kg	IFPRI Malawi Report, 2020
Cotton	998.00	Selina Wamucii, Malawi 2018
Cowpea	361.84	ACE Malawi, 2021
Pigeonpea	317.14	ACE Malawi, 2021

Groundnut	554.74	ACE Malawi, 2021
Soybean	526.48	ACE Malawi, 2021
Market Product		
Bananas	64.07	Selina Wamucii, Tanzania, 2018
Cabbage	111.71	Selina Wamucii, Malawi, 2020
Cassava	271.30	Selina Wamucii, Malawi, 2020
Honey	3,191.72	Selina Wamucii, Malawi, 2019
Tilapia	383.01	Selina Wamucii, Malawi, 2019
Tomato	312.00	Selina Wamucii, Malawi, 2021

11.5.4 Basic Economic Requirements of the Family

In addition to farm related costs, families require cash for a range of additional needs, including school fees and additional food (Aberman, 2018). The following approximate budget for a rural family in Malawi was based off of budget percentages from the research and total household expenditures from the research of (Aberman, 2018 and Davies, 2006). The results of Table 20 were inputted in FarmDESIGN as “general costs” experienced by the farm.

Table 21: Basic Economic Requirements of the Family

Item	**Description**	**% of Budget**	**Approximate Price in MWK**
Healthcare	Prevention, hospitalization, and traditional healers	2%	6,212.60
Education	School fees	2%	6,212.60
Clothing & Household Items	i.e. clothes and/or cooking material	3%	9,318.90
Transportation	Bus and other means	1%	3,106.30
Non-durables	i.e. fuel, hygiene, mosquito nets, repair material, mortgage, other costs.	13%	9,318.90
		Total	**34,169.30**

11.6 Product Destination & Human Nutrition Module

Households give careful thought to what farmed products are consumed and what is sold (Aberman, 2018). For product destinations it was assumed that the family would first ensure that they were food sufficient. Secondly, that they would sell what is left to meet their basic economic needs and finally ensure that livestock were fed, some seeds were held for next season, and crop residue was available for fields (Aberman, 2018).

11.6.1 Assumptions Made for Destination of Farm Products

- **Assumed that family first looked to be food secure** (Aberman, 2018)**.**
- **For residue yield of crops:** It was assumed that all residue yield would remain on farm. The assumption is that residues can be designated to either 1) green manure or 2) as feed for animals.
- **Assumed that larger livestock (goats and pigs) were not killed for meat unless an emergency.** Therefore no meat is produced by the animal goat.
- **For fire wood:** It is assumed that if wood is necessary it will be gathered off farm.
- **For purchase:** It was assumed that the family would purchase some additional food at the market or through barter. Therefore the external crop, tomato, honey, and cassava were created.
- **For Crop agronomy and crop products** (make-up yield, nutrients and vitamins): Inputs were based on USDA data.
- **For Crop residue** (make-up of yield, nutrients, vitamins, and feed value): Inputs were based on the DataFeedipedia.

11.6.2 Household and their Basic Nutritional Requirements

The nutritional requirements of the family were estimated in FarmDESIGN. Daily calorie requirements were based on a reference intake for each family member.

Table 22: Mother Farm Minimum Household Caloric Needs

Household Makeup: Mother Farmer			
Household Member	Age	Status	Daily Calorie Needs
Male	48	Healthy	2,550
Female	45	Non pregnant or lactating	1,940
Daughter	22	Pregnant	2,708
Son	18	Healthy	2,755

Table 23 Baby Farm Minimum Household Caloric Needs

Household Makeup: Baby Farmer			
Household Member	Age	Status	Daily Calorie Needs
Female	38	Non pregnant or lactating	1,940
Daughter	18	Non pregnant or lactating	2,708
Son	18	Healthy	2,755
Son	13	Healthy	2,280
Son	8	Healthy	1,715

11.6.3 Food Patterns

The food pattern in FarmDESIGN is defined by consumed food groups, and their consumption through grams of fresh weight per consumer unit per day. The research of Gilbert (2017) and Aberman (2018) in Central rural Malawi, was used to create a typical Malawian diet (seen in Table 21).

Of the crops grown, soybean, groundnut, and maize are extremely important for feeding the farmers and their family and as a market commodity (Gilbert, 2017; Aberman, 2018). Therefore farmers normally feed their families first with these crops and what is left is sold. Cowpea and pigeonpea are commonly sold (Gilbert, 2017). As stated the Malawian diet is typically dominated by maize, with enough access to maize often being equated to food security for Malawians (Aberman, 2018). In line with previous research, the basis of a typical Malawian diet is a nsima porridge, made from maize. This is often eaten with groundnuts and soybeans that are raw or minimally processed. At times, some leafy greens are included. Tomatoes, onions, pumpkin, and small quantities of meat are purchased at the market to supplement the diet when possible (Aberman, 2018). From the poultry and livestock, eggs are eaten and goat milk is consumed when produced, commonly as chambiko, a soured milk. Livestock are seen as a way of saving cash and only slaughtered or sold when absolutely necessary (Aberman, 2018).

A slightly adapted table from Aberman (2018) can be seen in Table 21 where the total average consumed calories remained accurate as a baseline for the diet, with a previous category titled "miscellaneous" substituted for additional vegetables. For each food group, a reference item was used to calculate calories needed for each household member as a part of the human nutrition module in FarmDESIGN. The reference crops chosen to use were based on additional research of commonly consumed foods.

In FD food pattern is based on consumed per person grams in fresh weight. Therefore the kcal needed to be changed to this. This was done through the reference crop dietary energy and kcal to get the final grams. The calculation is:

Grams Fresh Matter = Average consumer kcal / Dietary energy of crop * 100

Table 24: Patterns of Food Consumption in Malawi

Food Group (Kennedy et al., 2010)	**Crop/Product**	**Source of Item**	**Average Consumed Calories (kcal)**	**Dietary Energy of reference crop**	**Calculated to grams in Fresh matter**
Cereals	Maize	Farm	1,605	365	439.73
Roots and Tubers	Cassava	Market	68	160	42.5
Pulses and Nuts	Soybean	Farm	132	446	29.59
Vegetables	Tomato	Market	29	16	181.25
Vegetables	Cabbage	Market	21	25	84
Fruits	Bananas	Market	15	89	16
Meat	Poultry meat	Mix	25	349	7.16
Fish	Tilapia	Market	14	96	14.58
Eggs	Chicken eggs	Farm	5	143	3.49
Milk and Dairy	Goat milk	Farm	4	64	6.25
Oils and Fats	Groundnuts	Farm	71	567	12.52
Sugars	Honey	Market	57	304	18.75
TOTALS			2,046		

11.7 Final Overview of Golomoti Mother Farm

The following Table (25), shows the final farm overview compiled from Tables 9-14 to create a farm representative of a Golomoti, Mother Trial Farmer.

Table 25: Overview for Golomoti Mother Farmer- FarmDESIGN Inputs

Golomoti Mother Farmer						
HOUSEHOLD						
Characteristic	**Total number**					
Members	4					
ANIMALS						
Chickens/	6					
Goats	4					
Pigs	1					
CROPS						
Crop	**Area (ha)**	**Labour (h/ha)**	**Grain Yield (Kg/ha)**	**Residue Yield (Kg/ha)**	**NPK Applied**	**Urea Applied**
Maize (fertilized)	0.38	984	4,000	695	69	69
Maize (unfertilized)	0.03	930	600	104	0	0
Cotton	0.45	949	1,208	530	0	0
Maize / Cowpea	0.32	1,200	2,100 (Maize) 1,000 (Cowpea)	175 (Maize) 630 (Cowpea)	69	69
Maize / Pigeonpea	0.008	1,200	3,900 (Maize) 640 (Pigeonpea)	325 (Maize) 1,920 (Pigeonpea)	69	69
Maize/groundnut/Pigeonpea (DLR System)	0.04	1,650	3,100 (Maize) 900 (Groundnut) 640 (Pigeonpea)	258 (Maize) 771 (Groundnut) 1,920 (Pigeonpea)	35	35
Groundnut / Pigeonpea (Doubled up Legumes)	0.015	1,332	1,330 (Groundnut) 640 (Pigeonpea)	1,114 (Groundnut) 1,920 (Pigeonpea)	0	0
Groundnut	0.03	1,338	1,650	1,414	0	0
Soybean	0.03	1,398	1,500	1,687	0	0
Cowpea	0.009	1,050	1,100	874	0	0
TOTALS	**1.31 ha**				**242 kg**	**242 kg**

11.8 Final Overview of Golomoti Baby Farm

The following Table (26), shows the final farm overview compiled from Tables 9-14 to create a farm representative of a Golomoti, Baby Trial Farmer.

Table 26: Overview for Golomoti Baby Farmer- FarmDESIGN Inputs

Golomoti Baby Farmer						
HOUSEHOLD						
Characteristic	**Total number**					
Members	5					
ANIMALS						
Chickens/	4					
Goats	4					
Ducks	3					
CROPS						
Crop	**Area (ha)**	**Labour (h/ha)**	**Grain Yield (Kg/ha)**	**Residue Yield (Kg/ha)**	**NPK Applied**	**Urea Applied**
Maize (fertilized)	0.41	984	4,000	695	69	69
Maize / Pigeonpea	0.47	1,200	3,900 (Maize) 640 (Pigeonpea)	325 (Maize) 1,920 (Pigeonpea)	69	69
Groundnut	0.22	1,338	1,650	1,414	0	0
Soybean	0.005	1,398	1,500	1,687	0	0
TOTALS	**1.11 ha**				**138 kg**	**138 kg**

12.0 PHASE 3: FINAL ANALYSIS

In the analysis phase comparisons will be carried out between treatment type. This will be done through comparison of FarmDESIGN generated balances (SOM balance, Labour balance, Free HH budget, and dietary energy deviation) and comparison of charted pareto optimal curves of the farms by taking different variables such as SOM balance and Labour balance.

Table 27: Metrics from FarmDESIGN

Category	**Indicators**	**Measure**
Environmental	Soil OM balance	Kg ha^{-1} $year^{-1}$
	Species Richness (Margalef Index)	Fraction
	Crop residue inputs	Kg ha^{-1} $year^{-1}$
	Nitrogen Fixation	Kg ha^{-1} $year^{-1}$
	Nitrogen (N) soil balance	Kg ha^{-1} $year^{-1}$
	Phosphorus (P) soil balance	Kg ha^{-1} $year^{-1}$
	Potassium (K) soil balance	Kg ha^{-1} $year^{-1}$
Social	Total on-farm labor required	Hr $year^{-1}$
	Total off-farm labor performed	Hr $year^{-1}$
	Hired labor	Hr $year^{-1}$
	Leisure time	Hr $year^{-1}$
Nutritional	Dietary energy yield	Persons ha^{-1} $year^{-1}$
	Supply of energy	Kcal
	Self-reliance (for energy)	(%)
	Nutritional functional diversity (FDDS)	Total
	Household dietary diversity score (HDDS)	Total
Economic	Farm net income	MWK $year^{-1}$
	Off-farm income	MWK $year^{-1}$
	Other expenditures	MWK $year^{-1}$
	Household free budget	MWK $year^{-1}$

Table 28: Balances from FarmDESIGN

Category	**Balance**	**Measure**
Environmental	Soil OM Balance	Kg ha^{-1} $year^{-1}$
Social	Leisure Time	Hr $year^{-1}$
Nutritional	Dietary Energy Yield	Persons ha^{-1} $year^{-1}$
Economic	Household Free Budget	MWK $year^{-1}$

12.1 Description of Balances

From the full set of generated indicators, a selection of four balances were chosen to assess the holistic standing of the farm (seen in Table 29). A description of the chosen balances follows:

12.1.1 Environmental: Soil OM balance

Soil Organic Matter balance refers to the difference between inputs of organic matter into the soil, and the losses of organic matter (Adelhart et al., 2020). In-flows of soil OM can be seen as added crop residue and manures, out-flows can be degradation of SOM, erosion, and the breakdown of OM supplied in manure. The rate of degradation is in relation to the set environmental parameters. Objectives can be set to maximize the soil OM (FarmDESIGN Manual, 2020). The soil OM balance can indicate the health of the soil, and the impact of the rates that applied green manure and manure has on the farm system.

12.1.2 Social: Leisure Time

The Social indicator of “Leisure time,” is a household level indicator used to understand the relationship of required working time for the household (FarmDESIGN Manual, 2020). The indicator of “leisure time” refers to the time left after required farm and off farm labour activities have been completed. This is calculated by taking the available working time for each family member and subtracting the working time needed for both on farm activities, including crop care, animal husbandry, and off-farm activities. Either minimizing working hours or maximizing leisure time can be used as an objective to understand the level of time a household spends working. For this research leisure time was chosen.

12.1.3 Nutritional: Dietary Energy Yield

To understand the nutritional standing of a farm multiple indicators can be used. For this research the nutritional yield was used, expressed in persons/ha/year (Gambart et al., 2020). Using the Dietary Energy Yield as an indicator which looks at the dietary energy supply of the products annually produced on one ha of land, compared to the recommended daily reference intake of a 30-year-old male multiplied over 365 days (FarmDESIGN Manual, 2020). The higher the Dietary Energy Yield is the more people that can be fed annually by the farm; therefore it is often used as an objective to maximize.

12.1.4 Economic: Household Free budget

The household free budget is the resulting sum of money available to the household. This is calculated by taking the total income from off-farm and farm activities and deducting total expenditures including both farm related and household related (FarmDESIGN Manual, 2020). It is can be set as an objective to maximize household free budget.

PART TWO

13.0 CASE STUDY ANALYSIS

13.1 Scenario 1: Baseline Performance of the Current Farms

The baseline scenario attempts to answer RO1, by first looking at two AfricaRISING treatment types, a mother and baby farmer, and holistically assessing the farm against four indicators which account for a farms environmental, social, nutritional, and economic standing.

13.1.1 Constraints to Scenario 1: Baseline

This scenario works to understand how farms are currently performing. It was not the goal of this scenario to make direct comparisons between the two, as farm configurations, family size, and livestock differ. However, it was still important to understand how current farms are performing and the potential influence that differences between the two treatment types, especially in configuration, may have on the overall farm standing.

It is also important to note that not all implemented SI activities farms may be receiving are tested here. Therefore some increases and or decreases in overall farm status could be different to the reality of AfricaRISING treatment farms. **Of the SI activities that AfricaRISING has implemented (See Table 1), this research will test the performance of: doubled up food legumes, cereal-legume intercropping, and optimized fertilizer application.**

Configurations of the two farms can be seen in Figure 24. Where the mother farmer clearly has adopted more “trial plots” than that of the baby farmer, including the adoption of more legume-configuration options. In addition, one of the biggest differences seen between the two farms is the space allocated to a cash crop (green) which is seen in the Mother Farm.

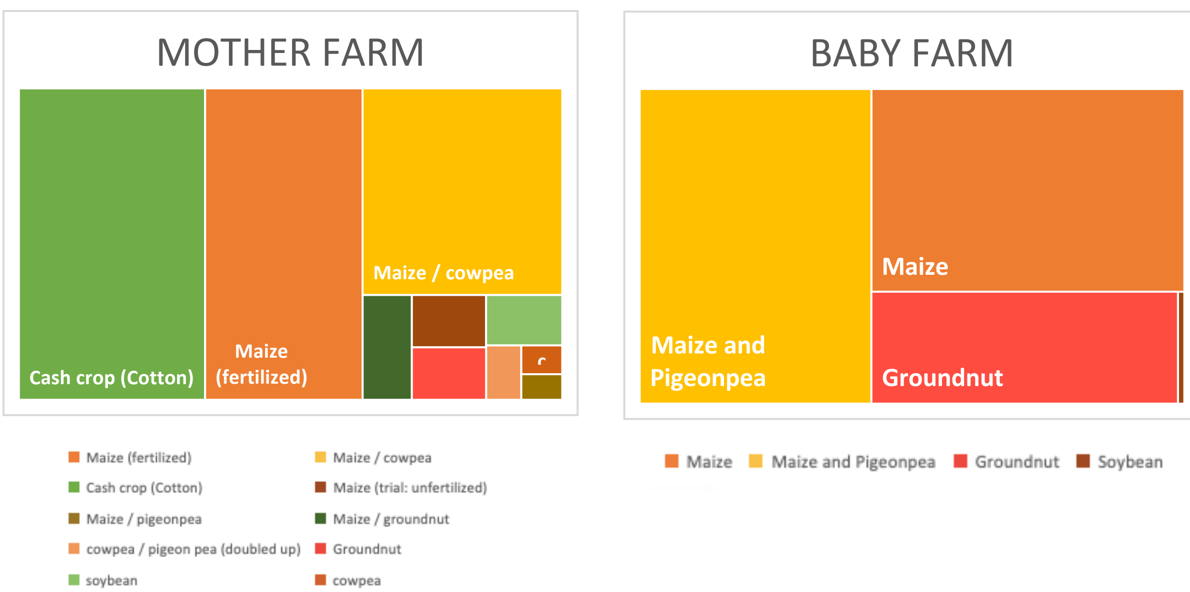


Fig. 24 Visualizations of farm configurations for Mother Farm (Left) and Baby Farm (Right)

SI trial plots being implemented by the mother farm include: doubled up food legumes with 0.015 hectares of legume-legume intercropping (groundnut and pigeonpea), and the adoption of DLR with 0.04 hectares of Maize, pigeonpea, and groundnut. Compared to the baby farmer that had no doubled-up food legumes or the innovative DLR configuration. With cereal-legume intercropping the mother farmer had implemented 0.008 hectares of maize-pigeonpea and 0.32 hectares of maize-cowpea (a total of 0.328). While the baby farmer, did have a larger total area dedicated to cereale-legume intercropping with 0.47 hectares dedicated to maize and pigeonpea. This was in line with the preliminary data analysis which showed that mother farmers although implementing more trial plots do not necessarily have more space dedicated to legume-intercropping. **With evidence seen that out of the total 54 farmers, mother farms on average had 0.27 hectares dedicated to legume intercropping while on average baby farmers had 0.31 hectares.** The baby farmer also had significant land set aside to sole crop legumes, a total of 0.225 hectares (groundnut and soybeans), while the mother farmer had a total of 0.069 (groundnut, soybean, and cowpea).

13.1.2 Scenario 1: Results

Looking at the two treatment types, results of the selected indicators can be seen in Table 29. Analysis of these results follow.

Table 29: Results of Selected Indicators

Category	Indicators	Baby Farmer	Mother Farmer	Measure
Environmental	Soil OM balance	344	89	Kg ha^{-1} year^{-1}
	Species Richness (Margalef Index)	0.322	0.9492	Fraction
	Crop residue inputs	696	808	Kg ha^{-1} year^{-1}
	Nitrogen Fixation	18	10	Kg ha^{-1} year^{-1}
	Nitrogen (N) soil balance	11	6	Kg ha^{-1} year^{-1}
	Phosphorus (P) soil balance	25	20	Kg ha^{-1} year^{-1}
	Potassium (K) soil balance	38	30	Kg ha^{-1} year^{-1}
Social	Total on-farm labor required (regular & casual)	2,800	3,527	Hr year^{-1}
	Total off-farm labor performed	0	400	Hr year^{-1}
	Hired labor	0	0	Hr year^{-1}
	Leisure time	417	626	Hr year^{-1}
Nutritional	Dietary energy yield	16.4	12.9	Persons ha^{-1} year^{-1}
	Supply of energy	4,507,506	5,033,465	kcal
	Self-reliance (for energy)	86	94	(%)
	Nutritional functional diversity (FDDS)*	12	12	Total
	Household dietary diversity score (HDDS)*	11	11	Total
Economic	Farm net income	592,626	1,317,839	MWK year^{-1}
	Off-farm income	0	2,800	MWK year^{-1}
	Costs for food	437,330	411,306	MWK year^{-1}
	Household free budget	155,296	909,332	MWK year^{-1}

Table 30: Results of Selected Balance Indicators

Category	Balance	Baby Farmer	Mother Farmer	Measure
Environmental	Soil OM balance	344	89	Kg ha^{-1} year^{-1}
Social	Leisure time	417	626	Hr year^{-1}
Nutritional	Dietary Energy Yield	16.4	12.9	Persons ha^{-1} year^{-1}
Economic	Household free budget	155,269	909,332	MWK year^{-1}

Environmental: In terms of environmental indicators it can be seen that the mother farmer (referred to as MF) has a higher level of species richness (due to MF's increased crop diversity). In terms of crop residue output and green manure the BF has more of both added to the fields, increasing the OM balance, which eventually could lead to higher levels of soil fertility (Timler et al., 2019). The baby farmer (BF) also has higher levels of nitrogen fixation most likely due its increased area dedicated to groundnuts and soybeans (Smith et al., 2016). Available manure, although not an indicator is marginally higher in that of MF as the farmer has more livestock.

Social: Between the MF and the BF, the BF farmer has lower rates of total required labour, which can partially be explained by its smaller cropping area. In addition the BF has adopted less labor-intensive configurations (such as DLR and legume-legume) (Komarek et al., 2018). Leisure time is seen to be greater in that of MF which is an indicator for social well-being of the farm, however leisure time is calculated on family available time, minus farm and off-farm labour time, and the MF household has more available time (a total of 3,527 hours) to that of the BF household (with 2,800 hours). Differences in available time are due to age and family member type, with the BF household lacking two full time farmers, as it is a female run household, also with the inclusion of younger children who are unable to work as much. Animal labour is seen to be the same, as both farms have labour associated to animal husbandry only with goats.

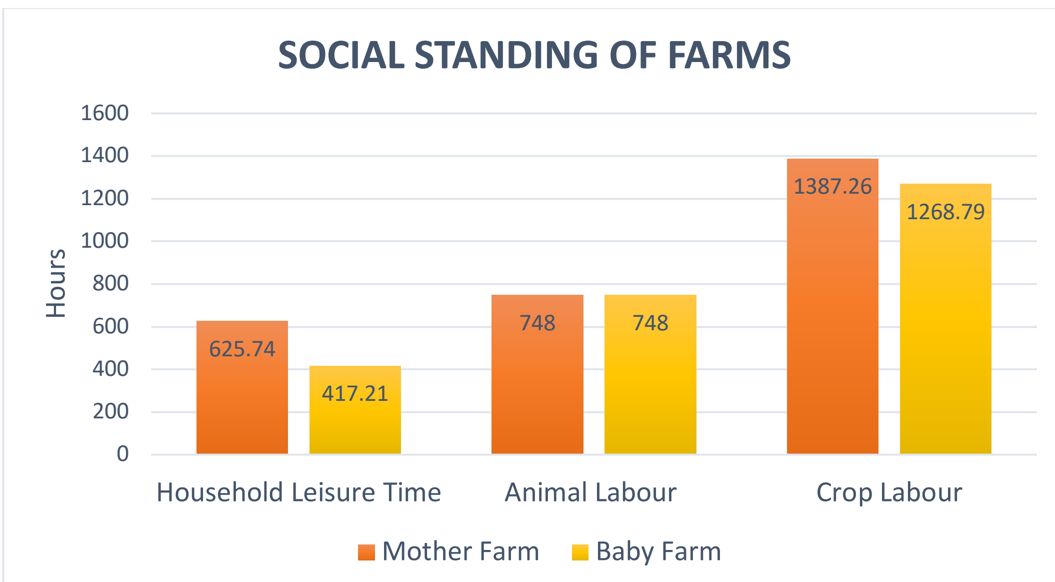


Fig. 25 Labour Distribution of the current Mother and Baby Farm

Nutritional: Overall the BF household has slightly higher levels of food and food security. The BF has in general a greater supply and access to farmed calories seen in the supply of energy, protein, and iron. As both households had the same set diet pattern and requirements, FDDS and HDDS were the same. This in reality may be different. Micronutrients such as Vitamin A, Iron, and Folic Acid however show up in higher levels with that of BF, which is interesting. This could be to the larger crop area dedicated to groundnuts and soybeans which are both high in micronutrients (Snapp et al., 2019).

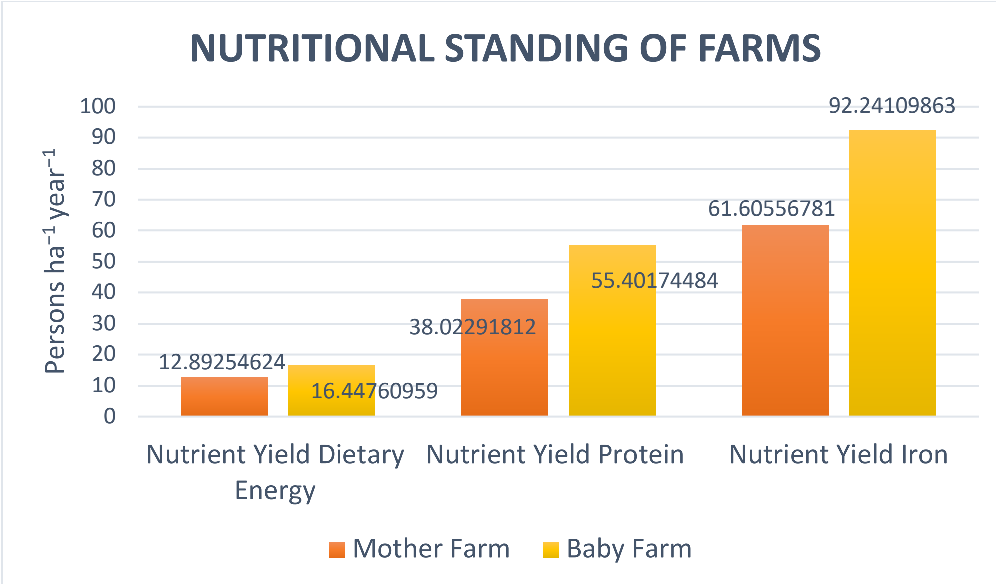


Fig. 26 Nutritional standing of the current Mother and Baby Farm

Economic: The economic standing of the MF farm is in general more secure than that of the BF farm. With higher levels of farm income and a greater household free budget. The difference in the MF farm's income is largely attributed to the large space dedicated to a cash crop, with the farm income dropping by 508,276 MWK when the area dedicated to cotton is removed.

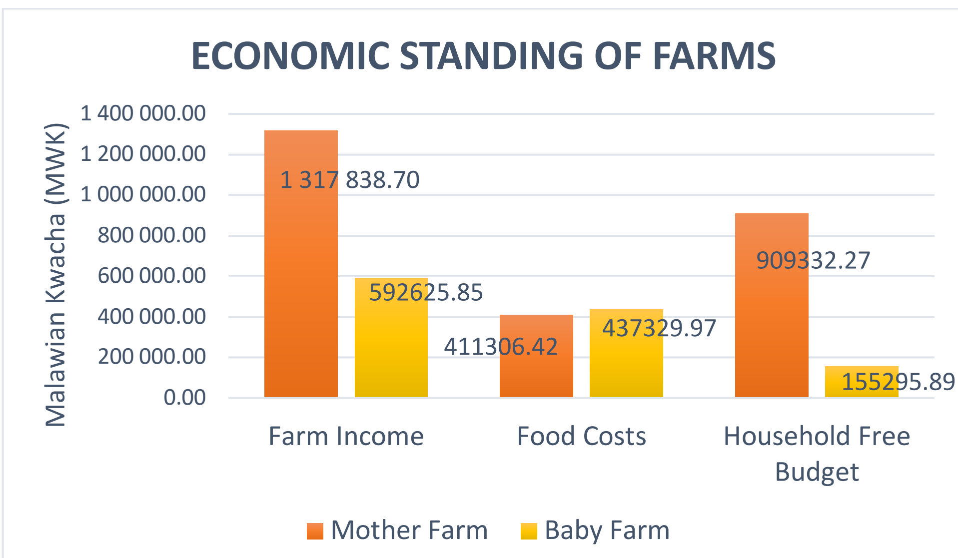


Fig. 27 Economic standing of the current Mother and Baby Farm

14.0 EXPLORATION

FarmDESIGN is whole-farm model which can quantify farm productivity, economic, environmental, and nutritional indicators on an annual basis (Groot et al., 2012). FarmDESIGN was used in both its static and exploratory form to analyze a representative mother and baby farm in Golomoti. Following the methods of Adelhart et al., 2020 and Ditzler et al., 2019, first a static evaluation of the current performance of the case study farms was done (Scenario 1), and then exploratory scenarios to optimize chosen objectives were run (Scenario 2-4).

In the exploratory phase, FarmDESIGN uses a Pareto-based Differential Evolution algorithm, to create farm configurations that meet a set of multiple objectives (Adelhart et al., 2020; Groot et al., 2012). In this phase (Scenarios 2-4), the original farm configurations were used and adapted with a set of constraints (to ensure the farm remained close to reality) so that FarmDESIGN could generate different configurations based on the objectives set. The exact constraints, decision variables, and objectives set for each scenario are explained in the following sections. However, in all scenarios the main point of freedom set for the model to change was that of cropping area. All objectives were based on the previously defined four holistic indicators of: (i) soil OM balance, (ii) household free budget, (iii) leisure time, and (iv) dietary energy yield.

14.0.1 Selection of Alternative Farm Configurations to View

Each scenario was run for both the mother and baby farm for 1000 iterations, using a mutation probability of 0.85 and a mutation amplitude of 0.15, with a set number of 500 solutions as parameters (recommended by Groot et al., 2007). This than generated a large set of alternative configurations which could be compared to the original baseline farm. From the cloud of generated solutions the following selection process was used to select configurations for further analysis:

1) The objectives output file, exported from FarmDESIGN, was inputted into excel and sorted for the highest and lowest performing farms for each objective. The best performing farm for each objective was than chosen.

2) The selected farms and their ID # were than checked with the ParetoOptimal output file, for its pareto optimal rank. As only farms with a rank of 1 were analyzed. To ensure that the selected farms were performing better in all 4 objectives than that of the original farm.

The four main scenarios were assessed. **Scenario 1)** A baseline analysis of the current farms as is. **Scenario 2)** An exploration of FarmDESIGN generated changes for both the mother and baby farmer based on the optimization of all four balance indicators. **Scenario 3)** FarmDESIGN generated configurations focused on farm adoption of more legume-intercropping area; and **Scenario 4)** FarmDESIGN generated configurations to optimize family nutrition.

14.1 Scenario 2: Optimization

Scenario 2 is an exploration of FarmDESIGN generated changes for both the mother and baby farmer based on the optimization of all four balance indicators being: environmental, social, nutritional, and economic. This allowed for the model to provide potential windows of opportunity in alternative farm configurations when optimizing all four of these indicators.

14.1.1 Decision Variables & Constraints:

As livestock are not a central component to the farms, the main decision variable focused on were that of crop and crop area. Therefore decision variables were set to allow for change in crop area and the destination of crop products (seen in Table 31). All objectives, decision variables, and constraints seen below were set the same for both the mother and baby farm.

Table 31: Objectives, Decision Variables, and Constraints set for Scenario 2

Objectives		
Maximize SOM (Environmental)		
Maximize Leisure time (Social)		
Maximize Dietary Energy Yield (Nutritional)		
Maximize household free budget (Economic)		
Decision Variables	**Minimum**	**Maximum**
Crop area	0	Total Current Crop area
Animal numbers	Current Farm #	Current Farm #
Destination of Crop products (to household or market)*	0 (kg DM)	30,000 (kg DM)
Destination of Crop residue (to green manure or animal feed)*	0 (kg DM)	30,000 (kg DM)
Grazing grass	0 (kg DM)	1,200 (kg DM)
Constraints	**Minimum**	**Maximum**
Whole Farm Crop Area (ha)	1.29 (MF); 1.083 (BF)	Current area
Field Area	1.29 (MF); 1.083 (BF)	Current area
Household Free Budget	0	Infinite
Organic Matter Balance	-310	Infinite
Saturation deviation	-infinite	0
Energy deviation	-5	5
Protein deviation	-10	32
Organic matter balance	-310	Infinite
Regular labour surplus	0	Infinite
Casual labour	0	Infinite
Leisure time	5	2065

*If only used on-farm, the decision variable set was 0 to 1, as a fraction

14.1.2 Scenario 2: Results

The following Tables (32-33) show the model generated configurations for selected farms. Farm selection followed the methods detailed in 14.0.1. For the MF, one can see that some synergies exist between optimizing Dietary Energy Yield (nutrition) and that of maximizing SOM (environmental), with the best performing configuration for these two indicators being the same farm. This farm (#179) has significant space allocated to DLR, which is interesting to see (also visualized in Fig. 28). This supports the conclusion that DLR is an SI technology that can be beneficial for a farms overall environmental and nutritional standing.

Table 32: Mother Farm: Baseline and Best Performing Configuration for Each Objective

Mother Farm Generated Configurations					
ID	Baseline*	#179 (Environmental)	#11 (Social)	#179 (Nutrition)	#420 (Economic)
Objectives					
Maximize SOM (Environmental)	89	**401.69**	115.84	401.69	382.35
Maximize Leisure time (Social)	626	450	**756.57**	450	467.54
Maximize Dietary Energy Yield (Nutritional)	12.9	24.67	9.88	**24.67**	24.12
Maximize household free budget (Economic)	909,332.00	1,333,214.82	518,209.25	1,333,214.82	**1,411,130.69**
Decision Variable					
Crop Area					
Maize35 area (ha)	0.03	0.00051	0.039	0.0051	0.54
Maize69 area (ha)	0.38	0.527	0.53	0.527	0.0017
Cotton area (ha)	0.45	0.00032	0.68	0.00032	0.02
Maize/Cowpea area (ha)	0.32	0.0012	0.0006	0.0012	0.0013
Maize/Pigeonpea area (ha)	0.008	0.0079	0.008	0.0079	0.008
DLR	0.04	0.75	0.0011	0.75	0.72
Groundnut/Pigeonpea	0.015	0.0042	0.008	0.0042	0.005
Groundnut	0.03	0.00069	0.0004	0.00069	0.0005
Soybean	0.03	0.018	0.017	0.018	0.016
Cowpea	0.009	0.00077	0.003	0.00077	0.0023

*Refers to the original farm configuration

All of the farms, besides the best performing for "social" have significant decreases in the cash crop area for cotton. This is especially surprising in the economic category, because cotton is a high earning crop. For the economic best performing farm, again DLR has significant area allocated with (0.72), supporting the benefits that DLR can provide farmers also economic returns. In general all farms have similar area set aside to maize, roughly just under half.

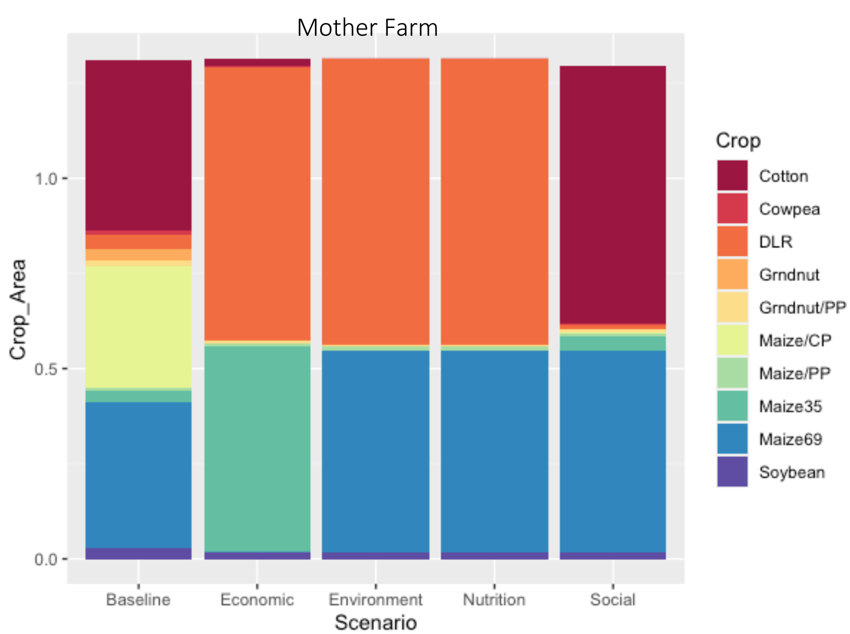


Fig. 28 Per Scenario: Crop Area Allocated by Hectare (Ha)

Table 33: Baby Farm: Baseline and Best Performing Configuration for Each Objective

Baby Farm Generated Configurations					
ID	Baseline	#150 (Environmental)	#336 (Social)	#495 (Nutrition)	#353 (Economic)
Objectives					
Maximize SOM (Environmental)	344	**486.50**	211.67	480.12	482.62
Maximize Leisure time (Social)	417	360.25	**553.80**	334.74	337.73
Maximize Dietary Energy Yield (Nutritional)	16.4	17.16	15.34	**17.48**	17.43
Maximize household free budget (Economic)	155,269.00	199,596.94	61,274.59	401,122.03	**411,330.00**
Decision Variable					
Crop Area					
Maize69 area (ha)	0.41	0.002	0.89	0.002	0.002
Maize/Pigeonpea area (ha)	0.47	0.89	0.0007	0.92	0.91
Groundnut	0.22	0.19	0.19	0.19	0.19
Soybean	0.005	0.0001	0.0001	0.00024	0.0001

Looking at the BF, in almost all categories (besides social), an increase in area dedicated to the intercropping of maize and pigeonpea was seen (Fig. 29). This was seen to increase both the environmental standing of the farm, the nutritional standing in available food, and the household free budget. Groundnut was also seen to be an important crop in all four objectives with 0.19 ha.

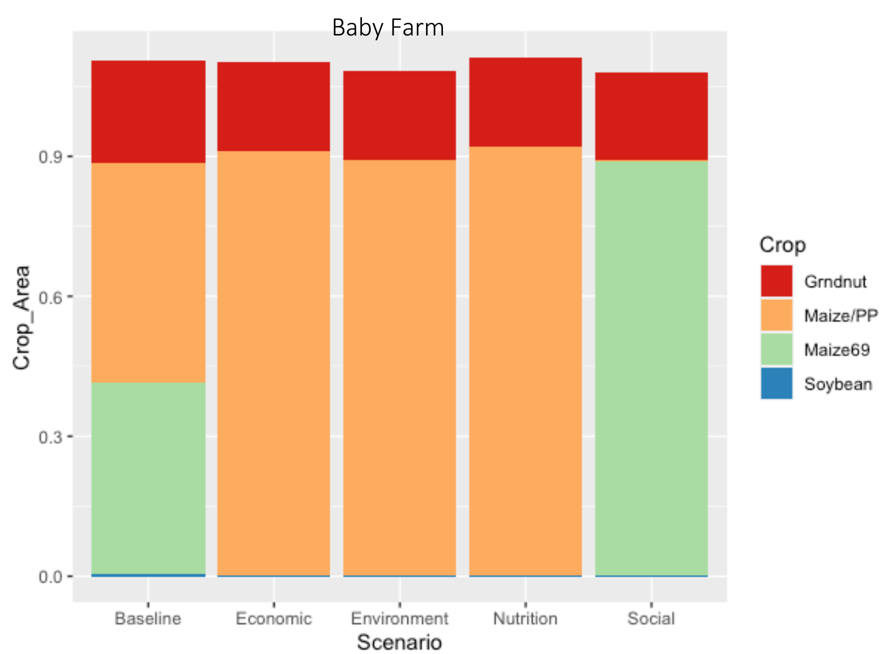


Fig. 29 Per Scenario: Crop Area Allocated by Hectare (Ha)

14.1.3 Scenario 2: Exploration of Solution Spaces

The FarmDESIGN generated solution spaces can show relations between the objectives of maximizing SOM, household leisure time, dietary energy yield and household free budget. Already in the MF a synergy between SOM and Dietary Energy Yield was found, based on the fact that the best performing farm for each objective was the same. This is also demonstrated in Fig. 30, where when OM increases an increase in dietary energy is also seen. In contrast the BF is seen to have less of a positive correlation, with relatively little increase or decrease seen between these two objectives.

A tradeoff in the solution space of the MF is also visible for that of HH leisure time and OM, with total household leisure time decreasing as OM increases. For the MF there seems to be much more distribution of solutions when it comes to HH free budget. However for both the MF and BF, household free time does not necessarily decrease with solutions that have the highest grossing HH free budget.

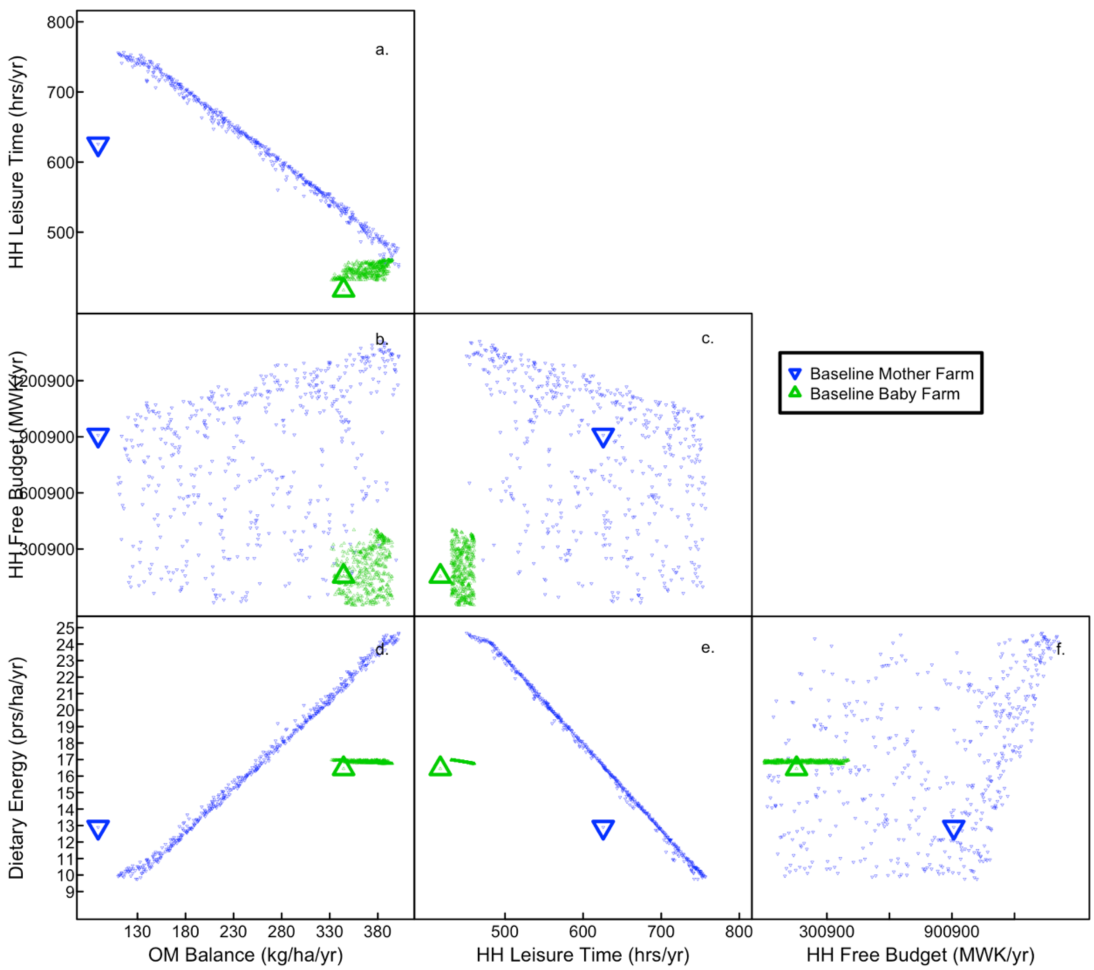


Fig. 30 Performance of alternative farm configurations in terms of four objectives, with the blue dots representing alternative farm configurations for the mother farm, and green for the baby farm. The baseline farm of each scenario is provided as a triangle.

14.2 Scenario 3: Legume-Intercropping

Scenario 3 was built to test the SI activity of legume-intercropping on farms, as this is a main component of the AfricaRISING project. Decision variables were set to allow for FarmDESIGN generated configurations to be created where the farmer adopts more legume-intercropping space.

14.2.1 Decision Variables & Constraints

Decision variables were set in a way to keep generated configurations close to reality, with cropping area of legume-intercropping allowed to increase by .10 hectares, and the total field area set to stay the same as current farms.

Table 34: Objectives, Decision Variables, and Constraints set for Scenario 3

Objectives		
Maximize SOM (Environmental)		
Maximize Leisure time (Social)		
Maximize Dietary Energy Yield (Nutritional)		
Maximize household free budget (Economic)		
Decision Variables	**Minimum**	**Maximum**
Crop area (legume-intercropping)	Current Crop area	Current Crop area + .10 ha
Crop area (non-legume-intercropping)	0	Current Crop area
Animal numbers	Current Farm #	Current Farm #
Destination of Crop products (to household or market)*	0 (kg DM)	30,000 (kg DM)
Destination of Crop residue (to green manure or animal feed)*	0 (kg DM)	30,000 (kg DM)
Grazing grass	0 (kg DM)	1,200 (kg DM)
Constraints	**Minimum**	**Maximum**
Whole Farm Crop Area (ha)	1.29 (MF); 1.083 (BF)	Current area
Field Area	1.29 (MF); 1.083 (BF)	Current area
Household Free Budget	0	Infinite
Organic Matter Balance	-310	Infinite
Saturation deviation	-infinite	0
Energy deviation	-5	5
Protein deviation	-10	32
Organic matter balance	-310	infinite
Regular labour surplus	0	infinite
Casual labour	0	infinite
Leisure time	5	2065

*if only used on-farm, the decision variable set was 0 to 1, as a fraction

14.2.2 Scenario 3: Results

The Results from this scenario were meant to understand the differences that may arise between the treatment types. Especially because the configuration of MF's has more trial plots, this scenario could point to potential effects if trial areas were increased. In addition, BF's will have more opportunity in this scenario to increase their legume-intercropping because they have more space within their farm already designated to legume-intercrop. Scenario 3 was run, however, in the end the results did not vary enough for it to be interesting for further analysis. Most likely this was due to the lack of movement allowed in the cropping constraints set. In the future it is potentially interesting to look at more "extreme" versions instead of only allowing for small increases.

14.3 Scenario 4: Optimize Profit & Nutrition

Scenario 4, explores FarmDESIGN generated configurations to optimize profit and family nutrition. Both of these indicators are key to the long-term adoption of SI activities. With profit and family nutrition a key component of food security, and as farmers in Malawi remain considerably vulnerable to periods of food insecurity, it is essential that SI activities introduced on farms increase experienced food security of households (Bezner Kerr et al., 2019; FAO et al., 2017). The indicator of dietary energy deviation and household free budget were used as indication for food security in the following explorations.

14.3.1 Decision Variables & Constraints:

Table 35: Objectives, Decision Variables, and Constraints set for Scenario 4

Objectives		
Maximize Dietary Energy Yield (Nutritional)		
Maximize Household Free Budget (Economic)		
Decision Variables	**Minimum**	**Maximum**
Crop area	0	Total Current Crop area
Animal numbers	Current Farm #	Current Farm #
Destination of Crop products (to household or market)*	0 (kg DM)	30,000 (kg DM)
Destination of Crop residue (to green manure or animal feed)*	0 (kg DM)	30,000 (kg DM)
Grazing grass	0 (kg DM)	1,200 (kg DM)
Constraints	**Minimum**	**Maximum**
Whole Farm Crop Area (ha)	1.29 (MF); 1.083 (BF)	Current area
Field Area	1.29 (MF); 1.083 (BF)	Current area
Household Free Budget	0	Infinite
Organic Matter Balance	-310	Infinite
Saturation deviation	-infinite	0
Energy deviation	-5	5
Protein deviation	-10	32
Organic matter balance	-310	infinite
Regular labour surplus	0	infinite
Casual labour	0	infinite
Leisure time	5	2065

*if only used on-farm, the decision variable set was 0 to 1, as a fraction

14.3.2 Scenario 4: Results

For optimizing Dietary Energy Yield, this is focused on feeding as many people as possible i.e. based on just calories, therefore the model allocated almost all the space to maize. However, this misses out on other important micro-nutrient indicators such as protein, iron, and vitamin A. Due to these results, another scenario (VN) was run that focused on optimizing the production of not just calories, but also protein, iron, and vitamin A (commonly cited indicators for what household members are lacking in their diet) (FAO et al., 2017).

For optimizing both dietary energy yield and household free budget, the best performing farm in the economic indicator allocated a majority to cotton and maize. This is not surprising as both crops have proven to be 1) sold at a higher price and 2) a way to produce the greatest number of calories.

Table 36: Mother Farm: Baseline and Best Performing Configuration for Each Objective

Mother Farm Generated Configurations				
ID	Baseline*	#58 (Nutrition)	#30 (Economic)	#81 (VN)
Objectives				
Maximize Dietary Energy Yield (Nutritional)	12.9	**19.46**	11.61	19.97
Maximize household free budget (Economic)	909,332.00	948,281.39	**1,127,838.92**	931,242.53
Maximize Protein Yield				**62.32**
Maximize Iron Yield				**103.78**
Maximize Vitamin A Yield				**34.97**
Decision Variable				
Crop Area				
Maize35 area (ha)	0.03	0.0001	0.00009	0.0004
Maize69 area (ha)	0.38	1.018	0.54	0.80
Cotton area (ha)	0.45	0.009	0.61	0.00008
Maize/Cowpea area (ha)	0.32	0.14	0.0009	0.32
Maize/Pigeonpea area (ha)	0.008	0.03	0.039	0.008
DLR	0.04	0.04	0.041	0.15
Groundnut/Pigeonpea	0.015	0.015	0.015	0.0003
Groundnut	0.03	0.028	0.028	0.0083
Soybean	0.03	0.029	0.029	0.03
Cowpea	0.009	0.009	0.009	0.0067

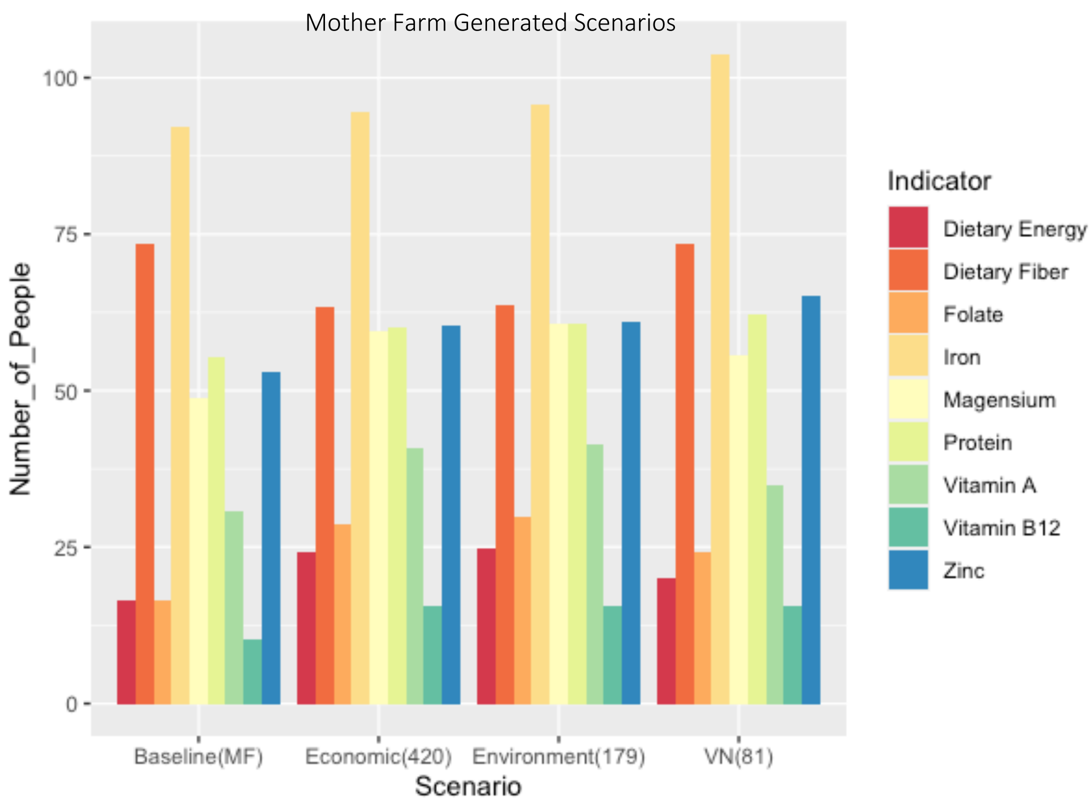


Fig. 31 Mother Farm Generated Scenarios for Economic and Environmental best performing farm configurations from Scenario 2, and a nutrition focused scenario (VN) from scenario 3.

In Figure 31, a set of key nutrition indicators were chosen. Scenarios explored were only done with the MF. The additional scenarios chosen were pulled from Scenario 2 where objectives were set to maximize dietary energy, household free budget, leisure time, and SOM. The selected configurations "Economic" and "Environment" were the best performing farms in each of these categories. In addition scenario "VN" was chosen as a contrast where objectives were set to maximize dietary energy, protein, iron, and vitamin A. Between the scenarios the variation is not as great as expected, with relatively similar levels of dietary energy and micronutrients.

Table 37: Baby Farm: Baseline and Best Performing Configuration for Each Objective

Baby Farm Generated Configurations			
ID	Baseline	#240 (Nutrition)	#14 (Economic)
Objectives			
Maximize Dietary Energy Yield (Nutritional)	16.4	**17.1**	15.16
Maximize Household Free Budget (Economic)	155,269.00	294,094.95	**397,766.84**
Decision Variable			
Crop Area			
Maize69 area (ha)	0.41	0.63	0.0015
Maize/Pigeonpea area (ha)	0.47	0.47	0.47
Groundnut	0.22	0.0004	0.63
Soybean	0.005	0.004	0.005

Objectives to maximize dietary energy yield and household free budget were also set and run for the baby farm. In Table 37, it is shown that the baby farm has potential for more dietary energy and household free budget to be generated. Examples of this are seen in configuration #240 and #14. In both of alternative configuration's emphasis was put on maize and pigeon pea intercrop, with groundnuts being shown as the more profitable crop in the best performing economic farm.

15.0 DISCUSSION

Results will be discussed by the phases of research, with phase one consisting of the preliminary statistical analysis, phase two results and assumptions when modeling in FarmDESIGN, and phase three, results and discussion points regarding overall findings from analysis. Points for further research, based on research findings will be stated at the end.

15.1 PHASE 1: Preliminary Statistical Analysis

From the preliminary statistical analysis initial findings were used to inform the further modeling of treatment types and exploratory scenarios to answer research objectives: RO1 and RO2. In addition to this, patterns regarding adoption of SI technologies also emerged which work to answer research objective: RO3.

15.1.1 Preliminary Statistical Analysis Results

Both literature and the AfricaRISING Malawi team emphasized the level of heterogeneity in both biophysical and socio-economic characteristics between smallholder farmers in Central Malawi (IITA, 2017; Snapp et al., 2002). This evidence, combined with the research of Timler et al., in 2013, which found that heterogeneity may exist to a lesser degree in Malawi than other sub-Saharan countries such as Tanzania, Ghana and Mali, all pointed to the need for additional research on smallholder farmers in Central Malawi. Therefore it was necessary to provide a statistical basis for the data set provided by the AfricaRISING MSU survey carried out over the 2019/2020 cropping seasons to understand current farmers and if heterogeneity within smallholder farmers was a true assumption. As typologies were not an aim of this research only a preliminary PCA was carried out.

The results from the PCA support the conclusion of prior research that there is heterogeneity between smallholder farmers. Clustering between farmers was clear, which indicates potentially significant differences between farmers even within the category of “smallholder.” The significance of these differences should be further analyzed for a deeper understanding of heterogeneity. This research can point to drivers of heterogeneity out of the chosen variables used for the PCA. These variables, being, that of total plots per farm, total hired hours, number of crops per farm, and total livestock. It is interesting that in this research the variables that drove the greatest variation were variables related to the actual configuration of the farms. However, these results could be influenced by the sample of farmers focused on the AfricaRISING treatment farms which have treatments that include very different configurations. Which would especially influence total plots per farm and number of crops per farm, as the mother trial farmers have more trial plots, and therefore more crops than that of the baby farmers.

The variables chosen for the PCA, can play a role in the clustering of farms that appear. Therefore it was important to choose a set of variables founded in prior research. The variables used were similar to that of (Timler et al., 2013) when carrying out farmer heterogeneity research in Malawi. Within the variables, the variable of “hired labour” was possibly inaccurate, as the labour data from Central Malawi proved to be difficult to accurately interpret. In future research a different variable for labour could be used, and a variable in reference to area dedicated to cash crops would be interesting. As farms that included cash crops or not come out as a major influencing factor on the economic standing of the farm.

15.1.2 Adoption Analysis

Adoption rates of SI activities in Central Malawi have remained low according to previous research (Jambo et al., 2019). Therefore it is important to understand a more recent analysis of drivers for adopting or opting out from the use SI technologies in farming management. To analyze this the AfricaRISING MSU 2019/2020 household survey was used, with focus on survey part 5, were questions regarding farmer's adoption of SI activities were answered.

It has been cited in literature repeatedly of the importance that an increase in yields has for adopting or sustaining SI practices (Ortega et al., 2016). This is again supported by this research, where the top cited reason for farmer adoption was that of "increasing yields." An increase of yields as a driving source for adoption is sensible, however it leaves a dangerous set of expectations where farmers may be disappointed and/or quit the SI technology when initial yields are not as expected. Therefore continued research should be carried out on the influence of SI technology on yields directly, as yields serve as a main indicator for farmers when adopting and sustaining such management practices. With more understanding of yield changes, farmers could be given a "blue print" for initial expectation and future yield changes in 2-5 years, when the long-term benefits of SI management may begin to be seen more clearly.

The top SI activities cited in this survey by farmers to adopt was that of drought tolerant crop varieties, maize-legume intercropping, and mulching crop residue. The main reason that farmers cited for not adopting SI activities was that of "confidence or uncertainty of the production benefits" which points to a need for continued knowledge and trust in SI to be built around these practices. It is interesting to note that the most cited SI activity that farmers actively chose not to adopt was DLR intercropping, as this is a core part of AfricaRISING's work. With again the main reason for not adopting being "confidence or uncertainty of the production benefits." Following this was fertilizer management. Therefore more knowledge surrounding DLR and the practice should be shared with farmers who are looking to transition their fields, so that a foundational understanding of mechanisms can increase confidence in farm felt benefits.

15.2 PHASE 2: FarmDESIGN

15.2.1 Constraints in Research

Some of the biggest constraints in research came with the required inputs for FarmDEISGN. A model can only operate as well as the data inputted, and FarmDESIGN requires a large amount of data inputs to run (Chiang, 2016; Groot et al., 2007). The most successful way to collect data for FarmDESIGN is collection through a tailored interview or survey for the model. However, this method is often not a reality. Evident with this research, where the survey intended to be used for the basis of modeling activities (AfricaRISING MSU 2019/2020 survey) was not appropriate for the data requirements. Therefore FarmDESIGN inputs had to come from not only survey responses but also prior scientific research and literature. This illustrates the difficulty in using survey data that is not specifically tailored for FarmDESIGN, and the constraints that arise with data collection in agriculture research.

As the collected data for the AfricaRISING MSU 2019/2020 survey had significant problems in harvest yield and labour, and lacked other necessary data. A majority of inputs for the model's components being: environmental, labour, crop, livestock, economic, product, and the human nutrition module were based from literature. However, both farm configurations in regards to cropping area, crop types, and livestock type and numbers were configured based off of AfricaRISING MSU 2019/2020 survey. A lack of field data for the modeled farms, and a reliance on literature for model inputs can affect the accuracy of results.

In addition to this, as one of the biggest indicators for system change is that of yield or harvest, not having harvest data from the farms proved to be the biggest challenge. To overcome this, grain and crop residue harvest for legume-intercropping were based off of the research of Smith et al., 2016. This again takes a step away from reality, as inputted harvest rates were based on a model generated harvest. The APSIM model does have a track record of predicting maize response to inorganic and organic N inputs, and effectively simulating competitive dynamics in both maize-legume and legume-legume intercropping configurations (Smith et al., 2016). The simulated maize and legume yields used were also specifically based from Golomoti and validated with field data from Golomoti. Smith et al., (2016) did however find that maize yields were at times under-predicted, but in most cases the model did accurately generate yield of groundnut, soybean, and pigeonpea (Smith et al., 2016). Another implication of using the results from Smith et al., was the impact this had on applied rates of inorganic fertilizer. By using the grain yields of generated from APSIM the rates of fertilizer applied had to follow the rates used by this research, therefore making the survey responses in the AfricaRISING MSU 2019/2020 survey not applicable.

With a lack of harvest data from the survey, the original research aims of analyzing differences between agro-ecological zones was also unable to be carried out. As the research of Smith et al., 2016 only focused on certain site locations. Initially the aim was to analyze both Golomoti and Balaka, as in the preliminary research these sites had arisen to have the greatest differences. However without harvest data for Balaka, this was unable to be completed. Future research should therefore address the variation seen between Golomoti and Balaka and the impact this variation has on SI activities at the farm-scale.

15.3 PHASE 3: Final Analysis

Overall, this research aimed to determine the potential farm-scale effects SI technologies can have on farms in Central Malawi, by holistically looking at the farms environmental, social, nutritional, and economic standing. It also looked to analyze farms by that of treatment group to understand how potential heterogeneity that can arise from treatment may lead to different reactions in response to implemented SI technologies.

Sustainable Intensification can mean a range of activities, due to realities in conducting this research the main SI activity assessed was that of space allocated to legume diversification. Legume diversification was seen in the crop configurations of DLR, legume-legume, and legume-maize. This study highlights the constraints and opportunities associated with the adoption of legumes by the two treatment types within the AfricaRISING project. Both farmers are also representative of a wider sub-set of smallholder farmers in Central Malawi.

Constraints and opportunities were modeled in FarmDESIGN with both an initial case study analysis of the current farms standing, followed by potential explorations of new farm configurations. This was able to demonstrate potential opportunities for farm configurations, and tradeoff and synergies with the adoption of legume-intercrops.

15.3.1 Case Study Analysis

The case study points to key differences between the AfricaRISING treatment types of mother and baby farmers which may be affecting the farms balance. With the two biggest differences being total space allocated to legume intercropping and the inclusion of a cash crop.

Between the two treatment types, mother farmers as a part of the project's structure have implemented more trial plots than that of baby farmers (IITA, 2017). In this, I assumed that mother farmers would therefore have more space in total allocated to legume intercropping configurations. However this assumption was wrong, with baby farmers on average having more total area dedicated to legume intercropping (supported also in section 3.0 Preliminary Analysis). This difference in total area dedicated to legume configurations is largely due to the space allocated to cash crops such as cotton or tobacco on their farm.

The case study analysis supports the conclusion that the mother farm is more resource endowed in terms of economics, which was also seen in the PCA (Fig. 3). With the mother farm having a significantly greater household free budget. With the financial gap between the baby farm and mother explained primarily by the inclusion of more cash crop area on the mother farm. When the cash crop is removed, and replaced by another crop (i.e. groundnut) the household free budget is significantly reduced and closer to that of the baby farm.

With how a farmer decides to configure their farm, i.e. space to a cash crop or space to legume intercropping, a clear tradeoff between economic, environmental and nutritional standing can be seen. The farmers with greater area dedicated to a cash crop are seen to have higher financial returns. However, with the example of the mother farm, tradeoffs are seen in regards to nutritional standing and environmental indicators. With the baby farm having higher levels of dietary energy, protein, and iron (Fig. 26). This may place mother farmers in a dangerous position, where yes they are making more money, but if a perturbation is felt such as drought, pests, or disease, and the cash crop fails, they are not as food secure from their own farm area (Peter, 2018).

In terms of the environmental situation of the mother and baby farm, the soil OM balance is surprisingly quite different between the two farms. Soil organic matter is essential for the supply of plant macronutrients N,P, and K and therefore is a key indication of overall soil health (Droppelmann, 2017). The OM balance is largely attributed to management practices and decisions based on where crop residue is allocated, either to animals, or returning the residues to the soil. As the AfricaRISING survey (MSU 2019/2020) had no data on rates of allocation of crop residues this was difficult to determine. In both farms there are low amounts of available crop residue, as livestock are also fed from this first, and the leftover crop residues were given to the field. This however may be different to reality. In addition, manure outputs are low and levels of applied organic and non-organic fertilizers are low as Central Malawi is a resource constrained setting.

Between the two farms, the baby farm is performing better in overall OM. This is due to the baby farmer having more green manure going to fields, most likely due to the differences in animals on the farms. Where the mother farm has more animals to feed. The mother farm does have more crop diversity, which diversity can also be seen as an important indicator. Higher levels of plant diversity have been associated with more resistance to pests and disease and higher resilience to drought (Tittonell, 2005). For both farms it is important for long-term productivity of the soil to be ensured that more organic matter and organic fertilizers are applied (Chikowo, 2014).

For the Hypothesis 1, stating that SI technologies implemented in farms will show improvements in a farms holistic system. It is difficult to make conclusions here, as both farms modeled were participants of the AfricaRISING project, and no control farm was modeled. In future, it would have been beneficial to model a control farm to understand farms that are doing no sustainable interventions. However the results of the case study analysis did provide an indication of the current standing of a representative farm for both treatment types in the project.

15.3.2 Explorations

For scenario exploration, the goal was to keep the scenarios as close to reality as possible. This is because the research aimed to provide improvements for farms in real life. However, because of this scenario's explored did not allow for "extremes" and FarmDESIGN generated configurations had less variation. This can be seen clearly in Scenario 3, which in the end did not provide applicable results, due to the fact that changes in configurations allowed were too small.

In Scenario 2 it was interesting to see how the model configured the farm. The focus on variables changed was that of crop area, because this variable is the most realistic thing farmers can change. While patterns of sold crop products to the animals most likely would follow the needs of the farmer. In the mother farm, a large area was reallocated to DLR (Fig. 24) in both the economic, environment, and nutrition optimized scenario. For social it was not, but DLR as stated in literature and documented can be more labour intensive. Conclusions from this can be made that an increase in DLR crop area will benefit a farms system. It can be similarly said that for the Baby Farm the model allocated again for the economic, environment, and nutrition scenario the most space to a legume-maize intercrop (Figure 25), with maize/PP). Supporting the conclusion of the benefits that legume-intercrops bring to a farm.

As seen in Scenario 1 a farm with more cropping area increases access to calories. However it was difficult to make the connection that legume-intercropping directly increases food security. Therefore further exploration was carried out in Scenario 4, to understand what configurations are best for optimizing household nutrition, and if more legume-intercropping corresponds directly to nutritional indicators. It can be said that the model did choose a significant area to be allocated to DLR. In the BF in all nutrition scenarios legume intercropping was also increased.

Looking at the results of Scenario 4, it was first run to maximize the objectives "dietary energy yield" and "household free budget", the results can be seen in Table 37, #58 and #30. For optimizing Dietary Energy Yield, this is focused on feeding as many people as possible i.e. based on just calories, therefore the model allocated almost all the space to maize. However, this misses out on other important micro-nutrient indicators such as protein, iron, and vitamin a. This also can speak to the mindset of most Malawians. Where the need has been focused on producing more food or calories, so the focus has been on maize production. However, this may meet a basic caloric requirement, but as seen in reality, this is leading to a host of micronutrient deficiencies, and also as seen in this is not building SOM (with farm #58).

Due to these results, I decided to look at a farm that focuses on optimizing the production of not just calories, but also protein, iron, and vitamin A (commonly cited indicators for what household members are lacking in their diet). When you add in other nutrition related objectives besides just dietary energy, in this case protein, iron, and vitamin A. The model still gave a significant area to maize, but also allocated quite a bit to a legume intercrop being maize – cowpea and also the DLR system. In comparison to the objective to only increase dietary energy yield and the economic where almost all of the land was allocated to maize. In this scenario, for alternative farm configuration #30, where the goal was to optimize economics, a large portion was given to Cotton. This again emphasizes the importance of a cash crop as a source of increased income for smallholder farmers. However with this, overall dietary energy yield significantly decreases from the baseline of (12.9 persons per hectare to 11.6).

15.4 Future Research

This research supports the conclusion of heterogeneity between smallholder farmers in Central Malawi. It can be seen between the three treatment groups (control, mother, and baby) that variation does arise both in geographic location and treatment. With the main points of difference coming from farm configuration. Potential different approaches in SI technologies implemented on a farm can come from an understanding of this. Therefore continued analysis on farmer heterogeneity and its statistical significance is recommended. In addition, an important point of variation is that of farmers that have cash crops or not. Therefore continued analysis on area allocated to cash crops and its influence on the farm system is recommending. Including potential different approaches within the AfricaRISING project to those farmers that have a cash crop or not. An initial element of this research was to assess DLR and legume intercrop configurations over a longer time scale. With the addition of agro-ecological zone comparison between Golomoti and Balaka. Although this was not carried out in this research due to constraints, both of these topics are recommended for further exploration.

16.0 CONCLUSION

Reinforced feedback loops at different scales have led to vulnerability and poverty in Southern Africa. This will likely only worsen due to the current state of land, resource dependency of the region, population growth, and climate change (Bezner Kerr et al., 2019 and Lade et al., 2017). Within the rural-agricultural landscape of Central Malawi, 65% of the land is affected by low soil fertility (FAO, 2016; UNCCD, 2016) and 94% of rural resident's livelihoods depend upon agriculture (Aberman, 2018). In addition to the current levels of land dependency, population rates are set to increase by roughly 3.3% within the region (Snapp et al., 2018 and World Bank, 2017). With increasing populations, the need for functioning resources and the optimization of these resource ecosystem service outputs must be improved to sustain livelihoods and food provision for a growing population (Falkenmark and Rockström, 2008).

To address this, agroecological methods have been implemented as a way to re-build soils and increase a variety of farm related indicators. However an understanding of SI and its impact on the whole farm is still difficult to unpack. An emphasis in research has been placed on environmental aspects but it is also important to understand SI implications for indicators beyond this. Especially in a context like Malawi, where so much of the agriculture and food security has culturally and traditionally been dependent upon Maize (Aberman, 2018).

Introducing SI within Maize dominated farms can therefore lead to spillover effects that effect the economic, social, and nutritional standing of a farm. Documenting these effects is essential for long term adoption of SI. As it is farmers that must sustain SI technologies, and if economic, social, or nutritional changes being felt are negative or positive this can severely influence adoption. It is also important to know so farmers can be presented with evidence for SI technology results, and expected outcomes and potential hurtles a farmer may face when beginning to adopt SI.

This research therefore contributed to the evidence surrounding maize-legume, legume-legume intercropping configurations. With an initial case study comparison carried out between the two treatment types within the AfricaRISING project, it is evident that farms that adopt more space for legume intercrop are performing better in environmental and nutritional indicators. Also seen here was the tradeoff between adopting a cash crop, where less space is than available on the farm for legume intercropping but the farm is most likely grossing greater financial returns due to the cash crop. The explorations carried out with FarmDESING demonst potential solution spaces for farm configurations that can increase environmental, economic, nutritional, and social standing of a farm. Furthermore it was seen of the significant place that DLR can have within a farm for improving overall standing. In addition, in the explorations carried out almost all scenarios involving economic, environmental, and nutritional indicators FarmDESIGN chose to expand crop areas of legume intercrops.

ANNEX 1: ADOPTION ANALYSIS

Adoption Analysis of Farmers in Central Malawi								
Activities	**Total # of farmer adoption**	**% of farmers Implementing***	**Top reason for adoption**	**Total # of farmers NOT adopted**	**% of farmers NOT adopted****	**Top reason for NOT adopting**	**# of farmers that stopped adoption**	**Reason why**
Drought tolerant crop varieties	49	91%	Increased yield (53%) Stress tolerant (18%) Increases yields (16%)	5	9%	Seed availability	8	Seed availability
Maize-legume intercropping	48	89%	Increased yield (48%) Improves soil fertility (33%) Saves labour (6%)	6	11%	Confidence or uncertainty of the product (67%) Seed availability Other	6	Expected productivity relative to conventional practices Seed availability Plots distance from residence Competition for labour outside the household Confidence or uncertainty
Crop rotation	39	72%	Improves soil fertility (36%) Increased yield (26%) Reduce build up of pathogens and pests in the soil (13%)	11	20%	Confidence or uncertainity of the product Expected productivity relative to conventioal practices	3	Asspcoated costs/financial Other Seed availability
Residue retention	Only one farmer practicing this, who heard it from the radio							
Herbicide use	14	26%	Controls weeds (36%) Helps control weeds (36%)	13	24%	Herbicide availability or access	1	Seed availability
Zero or minimum tillage	8	15%	Controls weeds Reduces soil erosion	7	13%	Confidence or uncertainity of the production benefits	0	N/A
Mulching crop residue	43	80%	Increased yield (19%) Reduced soil moisture loss (14%) Improve soil fertility (9%)	10	19%	Competition for labour ourside the household Competition for residue outside the household Competition for labour outside the household	0	N/A
Fertilizer management	25	46%	Reduced need for	12	22%	Confidence or	1	other

			fertilizer (52%) Increase fertilizer use efficiency in nutrient reduction (24%) Increases yield (12%)			uncertainty of the production benefits		
DLR	32	59%	Improves soil fertility Increases yield	21	39%	Confidence or uncertainty of the production benefits	0	N/A
Improved beans	4	7%	Improves soil fertility	3	6%	Seed availability	1	Seed availability

ANNEX 2: LABOUR CALCULATIONS FOR INTERCROP CONFIGURATIONS

SOLE CROP							
Activity	Cowpea	Pigeonpea*	Soybean	Groundnut	Maize	Maize unfertilized	**SOURCE**
Land Cultivation	50	50	54	50	50	50	**(Ojiem et al., 2014)**
Planting	12	12	17	11	10	10	**(Franke et al., 2010)**
Fertilizer	0	0	0	0	9	0	**(Ojiem et al., 2014)**
Weeding	36	36	36	36	25	25	**(Franke et al., 2006)**
Weeding	30	30	30	30	21	21	**83% of the first weeding**
Weeding	16	16	16	16	14	14	**(Ojiem et al., 2014)**
Harvest	14	14	34	34	12	12	**(Franke et al., 2010)**
Threshing	17	17	46	46	23	23	**(Franke et al., 2006)**
TOTAL	**175**	**175**	**233**	**223**	**164**	**155**	

CALCULATIONS

For Maize intercropped with Cowpea or Pigeonpea:

	Cowpea	1/2 cowpea	Maize	1/2 Maize	**Combined**
Land Cultivation	50	25	50	25	**50**
Planting	12	8.16	10	6.8	**14.96**
Fertilizer	0	0	9	6.12	**6.12**
Weeding	36	24.48	25	17	**41.48**
Weeding	30	20.4	21	14.28	**34.68**
Weeding	16	10.88	14	9.52	**20.4**
Harvest	14	7	12	6	**13**
Threshing	17	8.5	23	11.5	**20**
**Caluclated at 68%*					
TOTAL					**200.64**

For DLR Groundnut/Pigeonpea with Maize:

	Groundnut	1/3 Groundnut	Pigeonpea	1/3 Pigeonpea	Maize	1/3 Maize	**Combined**
Land Cultivation	50	16	50	16	50	16	**48**
Planting	11	5.28	12	5.76	10	4.8	**15.84**
Fertilizer	0	0	0	0	9	3	**3**
Weeding	36	17.28	36	17.28	25	12	**46.56**
Weeding	30	14.4	30	14.4	21	10.08	**38.88**
Weeding	16	7.68	16	7.68	14	6.72	**22.08**
Harvest	34	11	14	4.6	12	4	**19.6**
Threshing	46	15	17	5.6	23	7.6	**28.2**
**Caluclated at 48%*							**222.16**
TOTAL							

For Doubled up legumes (Pigeonpea / Groundnut):

	Pigeonpea	1/2 Pigeonpea	Groundnut	1/2 Groundnut	**Combined**
Land Cultivation	50	25	50	25	**50**
Planting	12	8.16	11	5.5	**13.66**
Fertilizer	0	0	0	0	**0**
Weeding	36	24.48	36	24.48	**48.96**
Weeding	30	20.4	30	20.4	**40.8**
Weeding	16	10.88	16	10.88	**21.76**
Harvest	14	7	34	17	**24**
Threshing	17	8.5	46	23	**31.5**
**Caluclated at 68%*					
TOTAL					**230.68**

ANNEX 3: BASIS OF YIELDS

Here the basis of yields data can be seen when in reference to Smith et al., 2016. The following was used to determine yields seen in Table 14.

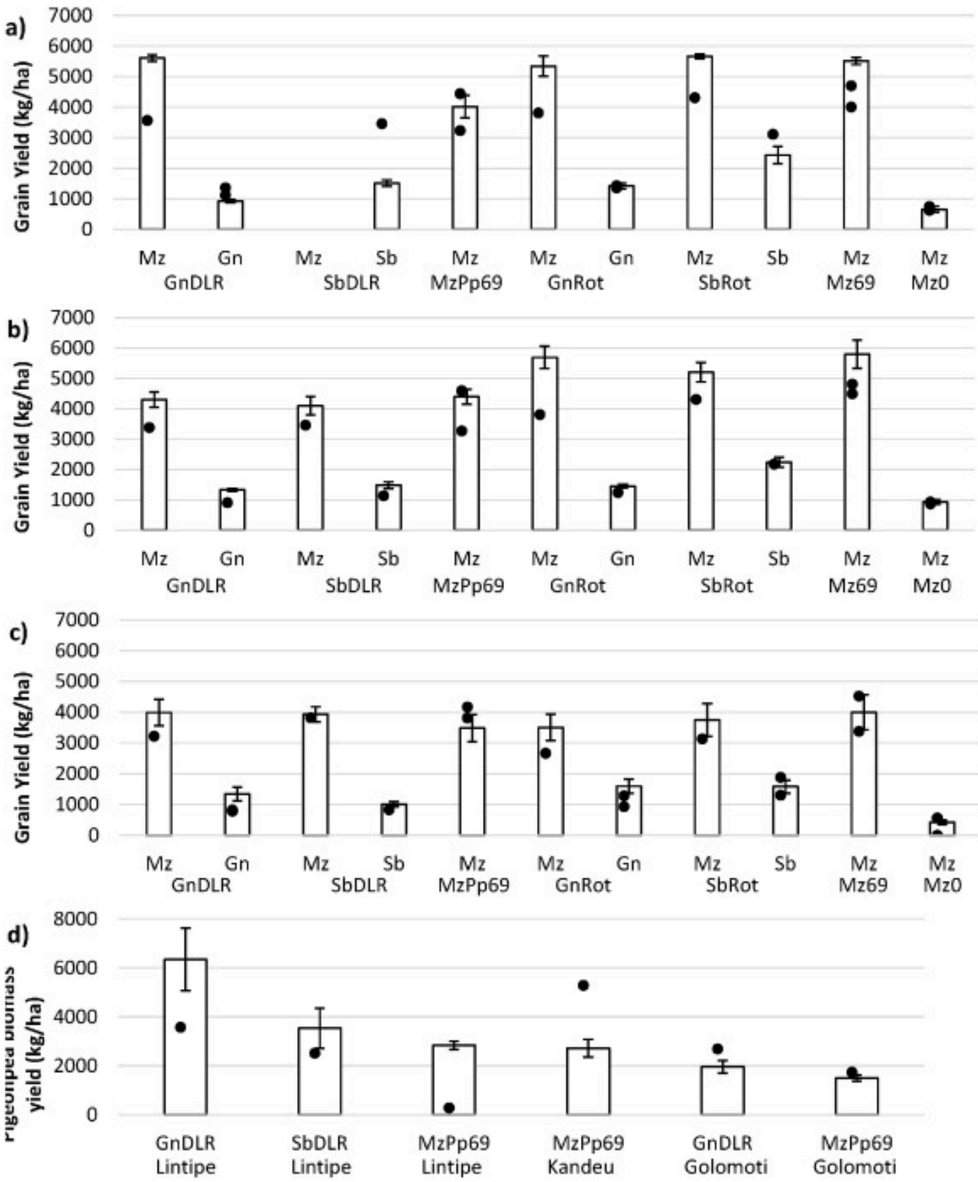


Fig. 1. Results of model calibration for maize, groundnut and soybean grain yields at a) Lintipe, b) Kandeu and c) Golomoti, as well as d) pigeonpea biomass yields at all three locations. Crops are abbreviated as Mz = maize, Gn = groundnut, and Sb = soybean. Bars represent observed yields from field experiments, with error bars showing standard error. Dots represent modeled yields. Bars with a single dot include yields from only a single growing season, while bars with two dots include yields for both the 2012–2013 and 2013–2014 growing seasons. Cropping system abbreviations are given in Table 1.

ANNEX 3 CONT.: BASIS OF YIELDS

Table 1: Grain yields of pigeonpea and groundnut grown as sole crops or as a doubled-up technology

Cropping system	Grain yield (kg/ha)	LER
Sole groundnut	1650	
Intercropped groundnut	1330	
		1.48
Sole pigeonpea	950	
Intercropped pigeonpea	640	

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